Hydrogeology

of the

Mackenzie Basin

Volume One: Thesis

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by

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Frontispiece: Mt Cook and Lake Pukaki

"I need here scarcely point out that it would be very important to have all the obtainable information as to the underground water supply of the district carefully collected, and mapped, and sections prepared. Such documents would be of the greatest usefulness, their study leading us to conclusions the value of which cannot be overestimated."

Sir Julius Von Haast
Provincial Geologist, 1879

ABSTRACT

The intermontane Mackenzie Basin is located within the central South Island of New Zealand. The glacial basin contains three glacial lakes which are used for hydroelectric power generation via a canal system that links the lakes. The basin is an area of climate extremes, low rainfall, high summer temperatures, and snowy winters. The area is predominantly used for pastoral farming, however farming practices are changing and, combined with an increasing population, there is a need to define the groundwater resources to enable sustainable resource management.

Little is currently known about the hydrogeological system within the Mackenzie Basin, and what is known is from investigations carried out during the construction of the canal system from 1935 to 1985. There are four glacial formations that overlie Tertiary sequences and Torlesse bedrock. However, due to the glacial processes that have been ongoing over at least the last 300 ka, determining the occurrence and extent of groundwater within the outwash gravels is difficult.

It is suggested that the permeability of the formations decreases with depth, therefore horizontal and vertical hydraulic conductivity decrease with depth. A shallow groundwater table is present within the Post Glacial Alluvial Gravels which is recharged directly from fast flowing streams and rivers as well as rainfall. It appears that this shallow system moves rapidly through the system and it is unlikely that the water infiltrates downwards to recharge the deeper groundwater system. It is thought that a deep groundwater system flows preferentially through the Mt John Outwash Gravels, being the second youngest glacial formation.

Water chemistry and age dating tracer analysis indicate that the deeper groundwater is over 80 years old and that the groundwater system is recharging slowly. The shallow groundwater in the Post Glacial Alluvial Gravels and within the major fans to the east of the basin is 10 to 20 years in age.

Baseline data such as water chemistry, groundwater levels, and surface water gaugings have been collected which can be used for future investigations. More data needs to be collected to create a long term record to further define the hydrogeological system and to determine the best way to manage the resource for long term sustainable use in the future.

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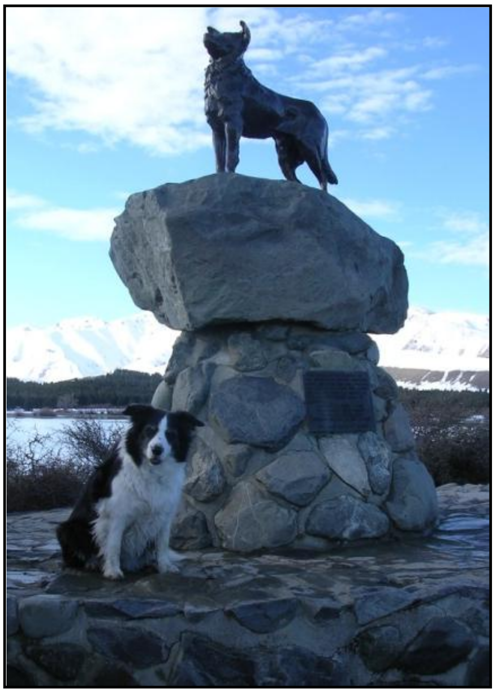

Lastly, but most importantly, to my family, thanks to Mum and Dad for all of your support moral, financial, and edible. Got there in the end!

To Richard – husband, co-university student, office mate, field assistant extraordinaire, walking dictionary, motivator, proof reader, and tea and toast bringer – your help and understanding has been the making of the last 6 years – now on to the next part...

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

The Mackenzie Basin is located in the Upper Waitaki catchment of the South Island, and has an area of approximately 700,000 hectares. The altitude of the basin ranges from 300 m to 600 m above sea level and is surrounded by the mountains of the Southern Alps to the west, with Mt Cook in the northwest rising to 3,754 m (Figure 1.1). The basin is an isolated area with regard to climate, farming practices, and lifestyle. The geology and geomorphology of the intermontane basin is dominated by the processes of past glacial ice advances. The complexity of these glacial processes has led to a highly variable stratigraphy and complex groundwater system.

Very little is known about the hydrogeology of the basin, and the information that is available has come from the hydroelectric projects constructed within the basin. As farming practices change throughout the South Canterbury area, increased demand for information about the hydrogeology and hydrology of the basin has arisen as farmers look to increase irrigation levels for the pastoral land. To assess the impact of these changes more information is required about the groundwater system. This thesis attempts to define the groundwater system through the collation of existing historical data together with the collection and interpretation of new data.

1.2 STUDY OBJECTIVES

The primary objective of this study is to document groundwater occurrences within the Mackenzie Basin, and to synthesise the current information for future investigations. The main objectives are to:

- Define the aquifer system within the Mackenzie Basin, determine the quantity of the groundwater resource, and determine its distribution throughout the basin
- Define baseline data such as recharge rates and water quality
- Develop a conceptual hydrogeological model for the Mackenzie Basin

1.3 STUDY AREA

The study area is approximately 1,300 km^2 within the Mackenzie Basin from Burkes Pass in the east to the eastern edge of Lake Ohau in the west (Figure 1.1). The area has been divided into two sub-basins for the purposes of the hydrogeological study; these being termed the Tekapo sub-basin and the Twizel sub-basin. The division is primarily defined by the bedrock outcrop of the Mary Range and Grays Hills which separates the two sub-basins hydrogeologically. In the north of the study area the upper extent has been defined using Braemar Road and the northward extension of the Mary Range. As a result, the upper boundary of the Tekapo sub-basin does not necessarily indicate a hydrogeological boundary as it is likely, in terms of the hydrogeological system, that this area extends further north to the foothills of the Gammack Range.

The Mackenzie Basin is bounded by the Rollesby Range and the Two Thumb Range in the east and the Ben Ohau Range in the west. The ranges are formed by the Torlesse Terrane, and the bedrock also outcrops at the centre of the basin forming the Mary Range. Overlying the Torlesse basement is the Glentanner Formation, which has been subsequently eroded and buried by glacial ice advances. Four separate advances are recognised, from oldest to youngest these are; the Wolds, Balmoral, Mt John, and Tekapo. These have left a glacial topography of lateral and terminal moraines and extensive outwash plains. The complex geomorphology is also illustrated by the extensive abandoned outwash channels that create a distinctive dendritic drainage pattern across the outwash plains.

The glacial basin contains three glacial lakes; Tekapo, Pukaki and Ohau, along with the man-made lakes Ruataniwha and Benmore. There is a substantial amount of surface water flowing through the basin in the fluvioglacial rivers and streams, and the main rivers are the Tekapo, Pukaki, and Ohau (Figure 1.1). The three major rivers that once drained the lakes are now generally dry in most reaches, only being fed by smaller rivers and streams, and during periods of over-spill from the dams.

The Mackenzie Basin is dominated by the hydroelectric dams and canals that were constructed during the period from 1935 to 1985. The area is predominantly used for sheep farming and hydroelectric generation, however dairy farming is now being considered as an option by many farmers in the area. The population of the Mackenzie Basin is approximately 5,000 and this appears to be increasing as the townships of Twizel and Lake Tekapo are attracting more residents.

Figure 1.1: Location map of the study area within the Mackenzie Basin. Dashed red line denotes the Twizel sub-basin, the dashed blue line denotes the Tekapo sub-basin.
(Inset: Maps indicate the location of the Mackenzie Basin within the South Island of New Zealand – dashed line indicates the extent of the study area (Coates, 2002; NIWA, 2008).

1.4 CLIMATE

The Mackenzie Basin is an area of climate extremes. The summers have high temperatures, with extremes reaching close to 40 ºC during February, while winters are cold bringing with them snow and hoar frosts. Data collected over a 60 year period (1941-2000), indicate that the mean annual temperature for Lake Tekapo was 9 °C with mean daily maximum temperatures in February of 23 °C and -3 °C in June. A sunshine average of 2,200 hours per annum has been recorded (NIWA, 2008).

The rainfall within the Mackenzie Basin has a small variation during the year, with slightly higher rainfalls recorded during the summer (Figure 1.2). It is likely that the slightly higher summer rainfall, particularly in the Twizel sub-basin, is due to warm north westerly winds (colloquially known as 'norwesters') that bring rainfall across the area. It has been noted, however, that although the variation within the year is low the variation between each year is greater making the amount of total rainfall prediction difficult (Waitaki Catchment Commission and Regional Water Board, 1982). Previous reports have considered the rainfall across the basin as fairly uniform when calculating water recharge estimates. However, rainfall sourced from specific directions (either northwest or southeast) tend to create variation across the basin. During the course of the study rainfall was observed to occur in large quantities in specific parts of the basin, predominantly close to the ranges in the west or the east.

Due to the close proximity of the Mackenzie Basin to the Southern Alps the area is affected by a rain shadow. The Southern Alps have the highest annual rainfall levels for New Zealand, estimated to be between 8 m and 15 m (Purdie, 2005). Total rainfall in 2007 at Mt Cook Village was 4,632 mm, compared to the total rainfall in Twizel of 377 mm in the same year. The distance between these two locations is approximately 60 km. Figure 1.3 indicates the pattern of rapidly decreasing rainfall levels as rain moves from the northwest towards the southeast. The mean yearly rainfall for the climate site at Lake Tekapo Airport for the period 1951 to 2007 was 598 mm. In Twizel the mean yearly rainfall was 525 mm for the period 1989 to 2002 (data from NIWA, 2008).

Unfortunately evapotranspiration has not been measured within the study area, but the Tara Hills climate site in Omarama (approximately 30 km south of the study area) does have a long record of climate data. The mean annual potential evapotranspiration rate (PET), the Penman PET method, is 871 mm based on data from 1951 to 2007 (data from NIWA, 2008). The mean annual rainfall at the same site, for the same period, was 518 mm. Figure 1.4 shows PET rates at Tara Hills in comparison to rainfall levels at Tara Hills and Lake Tekapo. The PET for Tara Hills is higher than rainfall for eight months of the year. The mean rainfall is approximately 80 mm higher at Lake Tekapo, therefore the PET rates calculated for Tara Hills could be used for calculations within the study area. The mean annual temperatures and sunshine hours are also comparable between the two sites. Mean annual potential evapotranspiration rates have been contoured (Figure 1.5). The contours are based on virtual climate sites using data from outside the Mackenzie Basin. The contours were created using a Fortran programme and gridded using the contouring software Surfer 8. There is a rapid increase of PET rates within the flat-lying areas of the basin in comparison to the surrounding mountains and ranges in the west and the east.

Rainfall events within the study area are often sporadic and intense. This trend, in conjunction with high summer temperatures, leads to high evapotranspiration rates removing much of the water from the surface that would otherwise recharge groundwater systems. The prevailing northwest winds and high summer temperatures often lead to extreme evaporation rates and droughts (Waitaki Catchment Commission and Regional Water Board, 1982). In addition, prevailing northwest winds during the spring and autumn desiccate the soils and contribute to wind erosion (Waitaki Catchment Commission and Regional Water Board, 1982). There is a sizeable amount of rainfall data that has been collected by farmers and government agencies within the Mackenzie Basin; however, the records tend to be discontinuous and for a short time period in some locations. The data has been collated for all of these sites and is contained in Appendix 1A.

1.5 SOILS AND VEGETATION

1.5.1 Soils

The types of soils present within the study area are shown in Figure 1.6. The soils have been reviewed extensively by the Soil Bureau (1968) and Webb (1992). Upland and high country yellow-brown earths are predominant in the Mackenzie Basin, and grade into yellow-grey earths in areas of drier climate.

Overall the soils are mostly coarse in texture, fine sandy loams to silt loams, and are often shallow or stony (Soil Bureau, 1968). The clay content within the soils can reach 20% in older more weathered soils. This soil profile prevents extensive soil moisture storage and limits plant growth. The profile available water represents the amount of water (in mm) that the soil can hold that is available for uptake by plants. The majority of the soils in the middle of the basin have an average profile available water of 20-50 mm, whereas the deeper soils around the edges of the basin have a profile available water of approximately 75-100 mm (Webb, 1992).

Due to intense ground frosts, high velocity winds and rainfall, the soils within the basin have a weakly developed structure, low bulk density, and are highly susceptible to wind and sheet erosion (Soil Bureau, 1968). Erosion has become more prevalent following the clearing of the land through burning of vegetation during the early Maori and European settlement period.

The permeability of the soils has been divided by Webb (1992) into low, moderate, and rapid infiltration of rainfall through the soil horizon. The soils have been grouped into four categories: soils on moraines which generally have a moderate to rapid permeability; soils on old terraces and fans that have a slow to rapid permeability; soils on young terraces and fans that have a moderate to rapid permeability; and soils on flood plains that have a slow to moderate permeability. Clay layers have also been observed, mainly within the soils on older terraces and fans, which will also reduce the ability of water to infiltrate downwards.

Webb (1992) states that the yellow-brown earths that overlie less permeable moraine deposits are formed from loess deposits that overlie the till. The reduced drainage in these areas provides a higher soil moisture content than in soils overlying the stony gravels on terraces and fans in the basin (Soil Bureau, 1968). The recent soils occupy floodplains and low terraces adjacent to rivers, and range from wet, stony, infertile soils to drier, deeper fertile silts (Waitaki Catchment Commission and Regional Water Board, 1982).

1.5.2 Vegetation

During the Holocene the climate led to the growth of scrub and small extents of forested areas within the Mackenzie Basin (McGlone & Moar, 1998). Grassland areas predominated within the basin following drought and scrub fires. Today the basin is dominated by fescue short-tussock grassland (Webb, 1992). In drier sites, the weed Hieracium is predominant. Areas of scrubland, on the sides of the ranges, contain mainly Matagouri (Waitaki Catchment Commission and Regional Water Board, 1982). Deeper soils have been converted to sown pasture, and on the fans in the east and west Lucerne is present. Vigorous vegetation growth is seen in swamp areas such as the southern reach of the Grays River and within the pro-glacial lake area within the Mary Burn course (Webb, 1992). Vegetation has continued to change even over the past 50 years: previously the tussock was much more extensive and dense compared to the present day (A. Shearer pers. comm., 2007). The reduction in plant growth is likely to be due to the extensive rabbit population within the area, changing farming practices, and/or a changing climate.

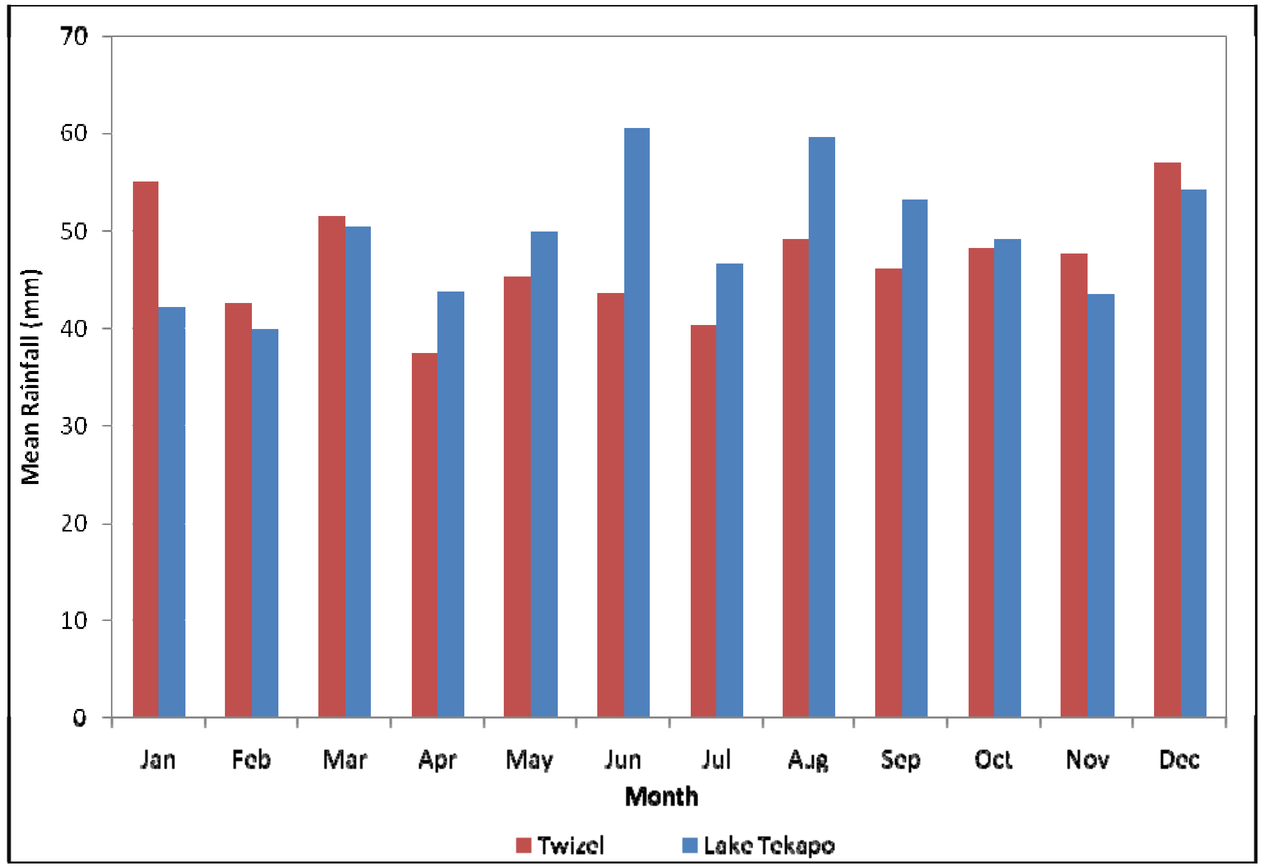


Figure 1.2: Comparison of mean annual rainfall between the climate sites at the Twizel and Lake Tekapo Airports. The data covers the period 1985 to 2002 (data source: NIWA, 2008).

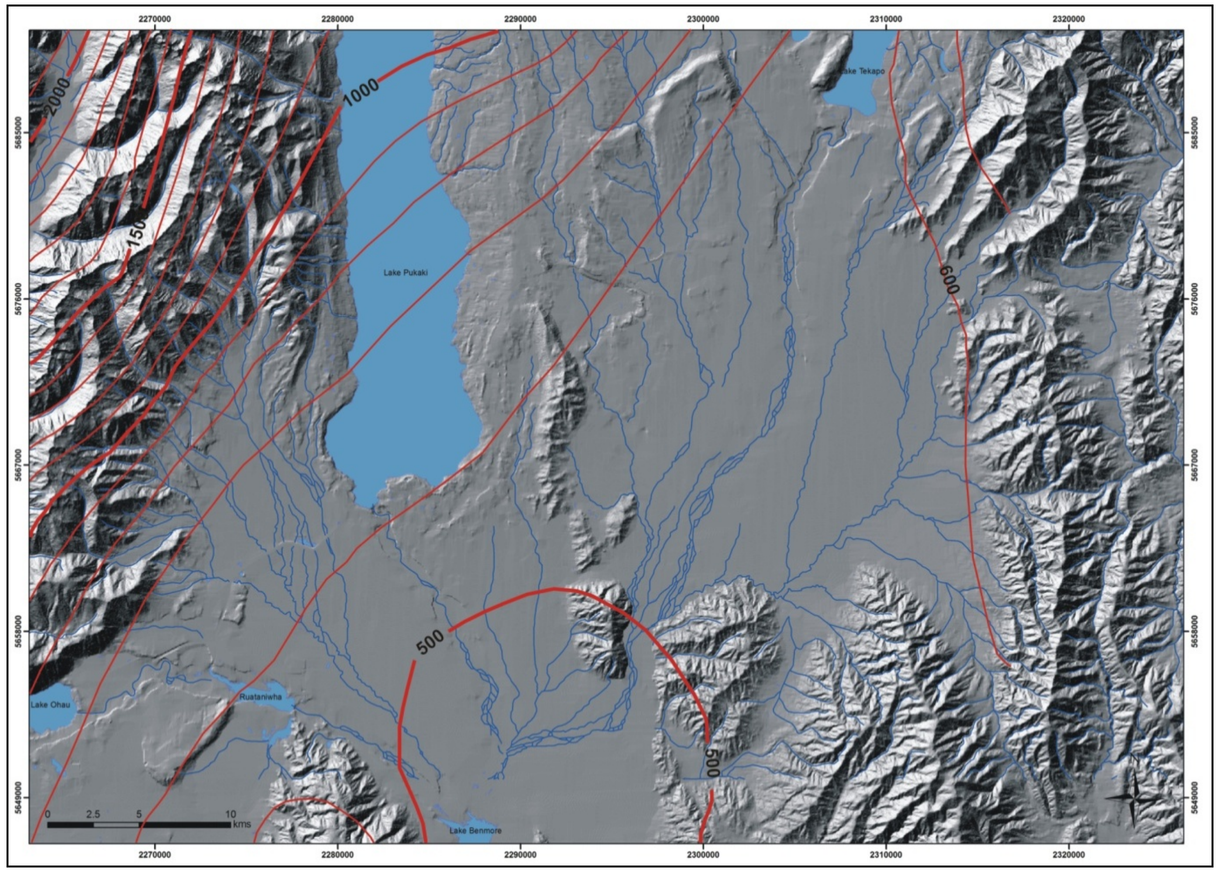


Figure 1.3: Mean annual rainfall (mm) contours based on data from 1972 to 2003. Contour lines have a 100 m interval.

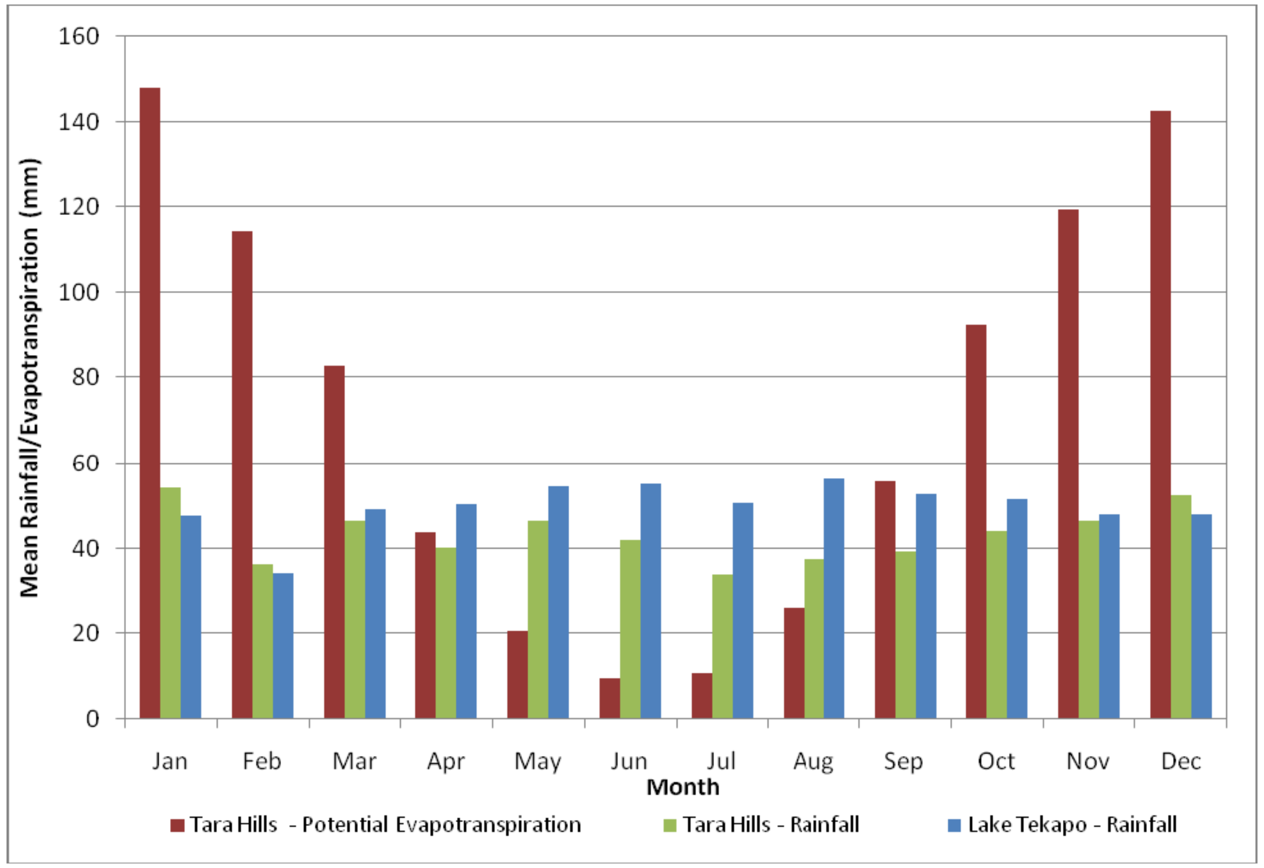


Figure 1.4: Comparison of potential evapotranspiration and rainfall at Tara Hills as well as rainfall at Lake Tekapo, The data covers the period 1951 to 2007 (data source: NIWA, 2008).

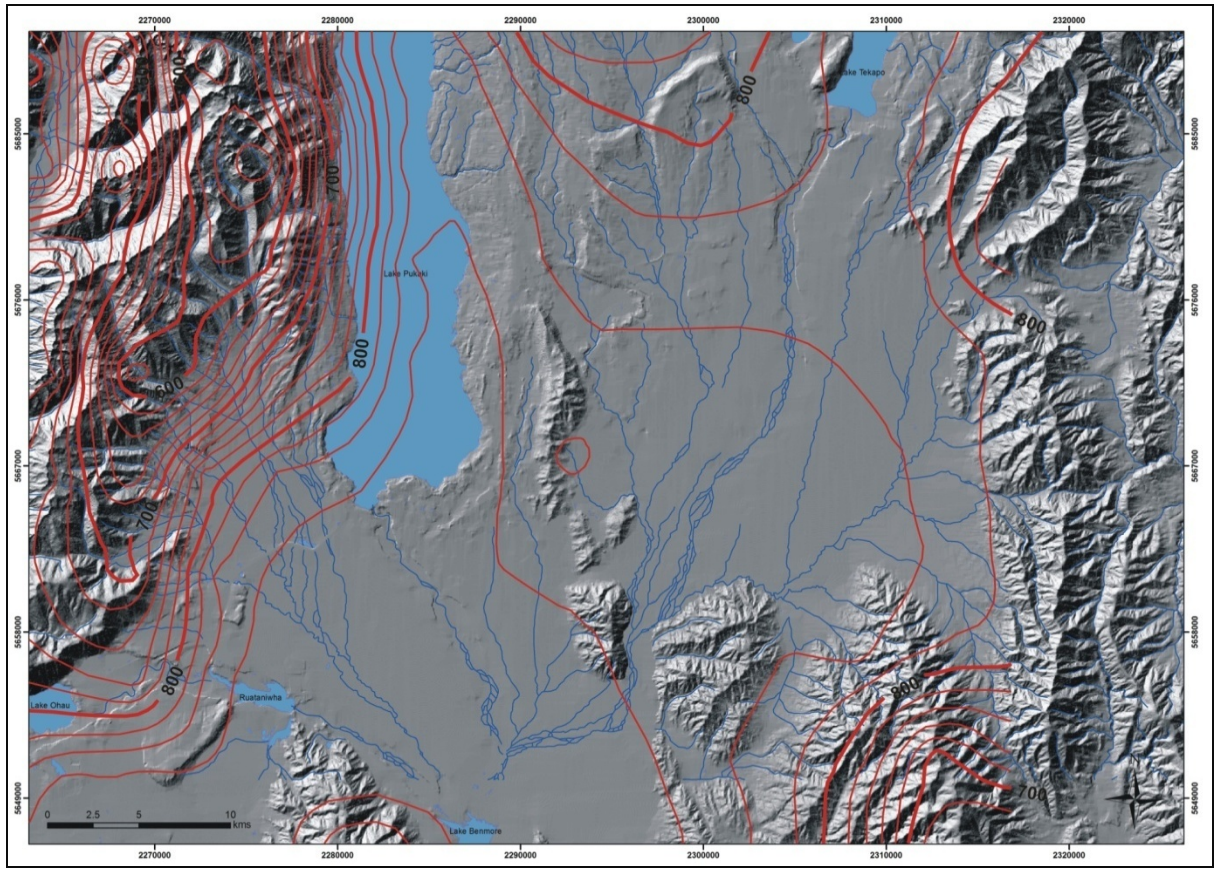


Figure 1.5: Mean annual potential evapotranspiration (mm) contours using virtual climate sites based on data from 1972 to 2003. Contour lines have a 20 m interval.

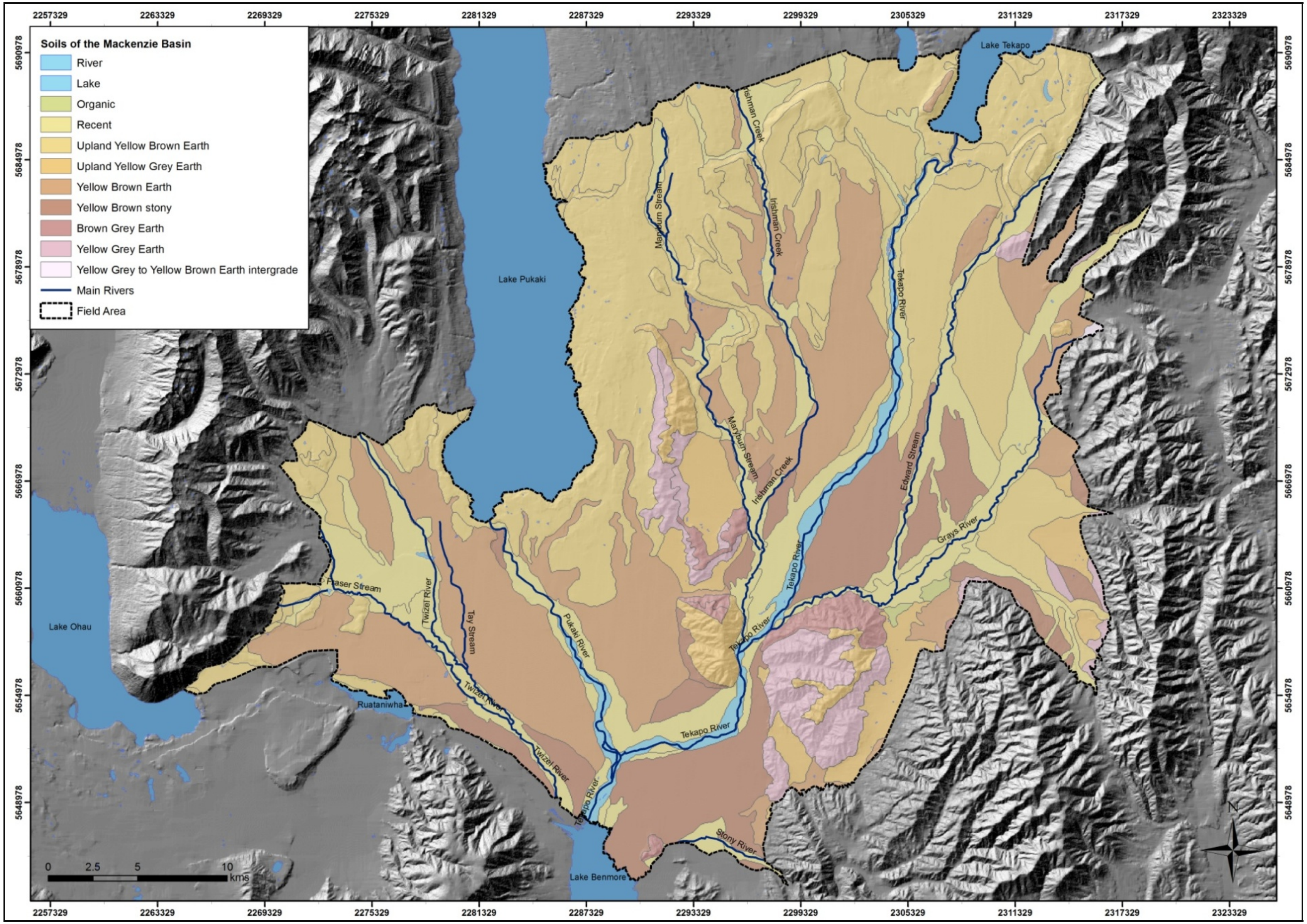


Figure 1.6: Soils map for the study area within the Mackenzie Basin.

1.6 LAND USE AND WATER DEVELOPMENT

The Mackenzie Basin was first settled by Maori prior to the arrival of European settlers. The Mackenzie Pass into the basin is thought to have been used for sheep rustling in the legend of James McKenzie; however there are several differing reports of this story (Whelan, 1989). In 1848 a block of land covering 20 million acres, which included the Mackenzie Basin, was acquired by the Crown. In 1853 14-year leases were issued to pastoral farmers. Land in the basin was first settled by European farmers in 1856, but these settlers lasted only a year and they were replaced by W H Ostler. By the 1860’s all of the land had been leased for a rent of 3 farthings per acre per year (Whelan, 1989). Most of the high country stations that were formed during the late 1800’s exist today, some with the descendants of those early farmers still working the stations.

Pastoral farming continues to the present day and merino sheep are bred for wool export purposes. During the 1930’s to 1950’s a decline in sheep numbers is thought to be due to the severe infestation of rabbits (Waitaki Catchment Commission and Regional Water Board, 1982). There are some areas of more intensive irrigation and during the 1970’s and 1980’s small irrigation schemes, such as the Maryburn irrigation scheme, were created.

Between 1935 and 1985 the population within the Mackenzie Basin grew during the construction of the hydroelectric dam and canal system. The three main rivers (Tekapo, Pukaki, and Ohau Rivers) were diverted to flow through the present day canal system. Each of the three glacial lakes (Lakes Tekapo, Pukaki, and Ohau) is linked by the canals (Figure 1.1). The area that was Benmore Gorge now contains the manmade Lake Benmore. The manmade Lake Ruataniwha was formed upon completion of the Ruataniwha Dam. Further downstream the Waitaki River was also dammed to create Lake Aviemore and Lake Waitaki. Five power stations have been built at the dams. The scheme comprises a total of eight power stations producing approximately 8,000 gigawatt-hours annually (Waitaki Catchment Water Allocation Board, 2005).

The canal system also provides high country stations with water on a limited basis for irrigation, stock water, and small-scale power generation. Surface water and springs provide the main source of stock water and irrigation for the area and wells are predominantly used for domestic and town water supplies. The most common form of irrigation is flood and border dyke systems, but spray irrigation is becoming more prevalent. The irrigation period is generally October to March/April in most areas. Consent applications have been submitted to enable more wells to be drilled for farming purposes. However, several deep wells that have recently been drilled have not encountered any groundwater (I37/0023) or produce insufficient water for irrigation use (I38/0012 and I38/0015).

As the population continues to grow in Twizel and Lake Tekapo townships more domestic wells are being installed. It has been observed to the east of Lake Tekapo that the flow of springs has reduced during the same period that new wells are drawing water from the groundwater system. The current town water supply for the township of Lake Tekapo is to the northwest, close to the Fork Stream. In Twizel the water supply is from three, approximately 20 m deep, wells within the active riverbed of the Fraser Stream. This water is then pumped to an open reservoir. However, the Twizel town water supply is currently under review.

In February 2007, 232 wells were listed within the study area in Environment Canterbury's wells database. Of these, only 54 were able to be located and have the groundwater levels measured (Figure 1.7). Over 150 of the wells listed on the database were old Ministry of Works observation pipes installed for investigation purposes during canal construction. Nearly all of these pipes have either been buried or removed. All of the Meridian Energy owned observation wells were also inaccessible. As of March 2008, there were 31 proposed wells that are yet to be drilled listed on the database. The bore logs for all of the wells that are present within the study area are included in Appendix 7B.

1.7 PREVIOUS WORK

Initial research was done in the early to mid 1900's on the regional geology of the area by various authors including Speight (1940), Speight (1961), and Gair (1967). Primarily the glacial formations present within the Mackenzie Basin and the active fault systems have been reviewed by these authors. The first geological map was produced by Gair (1967), who mapped the extent of the four separate glacial formations as part of the larger Mt Cook map sheet. More recently, a new geological map has been produced for the Aoraki area by Cox & Barrell (2007). Geomorphological mapping of the glacial moraines and other features is currently being done by Geological & Nuclear Sciences and an American research group.

Little work has been done to quantify groundwater resources in detail within the Mackenzie Basin. Early investigations were conducted to define the presence of groundwater that may adversely affect the construction of the dams and canal system. These investigations were generally spatially limited to the areas where canals were to be built. There are a number of resultant reports that include groundwater investigations and interpretations, authored by S. A. L. Read and D Macfarlane of the New Zealand Geological Survey during the 1970's and

1980's. Most of these reports have been used for the groundwater interpretation of this study and a summary of these reports are contained in Chapter Seven. A number of consultants' reports that have been completed in recent years are also summarised in Chapter Seven.

The other main focus of research has been on fault zones, major geological structural features, and the glacial geology of the area. The extensive literature regarding the geophysical investigations that have been conducted within the Mackenzie Basin have been summarised within Chapter Three.

A

B

C

D

Figure 1.7: Types of wells located within the study area. A) household water supply (H38/0188), B) old Ministry of Works observation pipe (I38/00045), C) 300 mm diameter irrigation well (H38/0035), D) flowing artesian well – old Ministry of Works observation pipe (H37/0009).

1.8 RESEARCH METHODS

Initially an introductory postal survey was sent to the 22 main High Country stations within the study area. The purpose of the survey was to inform residents of the purposes of the study and asked for any information regarding wells, springs, surface water use, and rainfall information that each station may have. Fifty percent of the surveys were returned. Following the survey each landowner was visited in person to follow up on this information. Several landowners did not wish to participate in this study for a variety of reasons, and therefore not all parts of the study area were accessible.

In February 2007 all of the wells noted on Environment Canterbury's wells database were visited for the purposes of collecting accurate location data. Water levels in all wells were measured and this data was used for a piezometric survey. Of the wells visited 46 were chosen for monthly monitoring and eight had water level loggers installed, which ran for either nine or twelve months. A barometric pressure logger was also installed in each sub-basin.

In June 2007 a gravity survey was undertaken across the Tekapo sub-basin to determine the depth to bedrock within this area. In July of the same year a time domain electro-magnetic (TEM) survey was conducted to ascertain whether any aquifers could be identified and to define the thickness of the glacial gravels within the Tekapo sub-basin. In March 2008 a small scale seismic survey was conducted on the east side of the Mary Range for the purposes of defining stratigraphic detail within the top 150 m of the subsurface. It was hoped that water-bearing channels would also be identified.

Water samples were collected in October 2007 from 21 locations for water chemistry analysis. The purpose of the analysis was primarily to provide baseline data, and to identify any anomalous sites. The chemical signatures of the water were also used to help interpret groundwater flow directions, and to group common chemical signatures in order to identify recharge sources. Nine samples were also collected for age and recharge source analysis to be done by Geological & Nuclear Sciences. The purpose of this analysis was to determine the age of the groundwater, and therefore to establish the approximate rate of recharge and residence time of the groundwater.

A spring survey was conducted in parts of the study area. However, only parts of the study area were covered due to the large extent of the area, the large number of springs, and the restriction of access in some areas. The purpose of the survey was to identify the types of springs present, and to identify any surface water/groundwater interaction.

Concurrent river gaugings were conducted from October 2007 until March 2008 by Environment Canterbury staff at 22 sites on a monthly basis. The data collected were combined with rainfall and groundwater level data to determine the influence (if any) of surface water flows on groundwater levels. The data was also used to define any gaining or losing reaches, and to quantify the amount of surface water that may contribute to the groundwater system.

1.9 THESIS FORMAT

The thesis is divided into eight chapters. Chapter Two summarises the geology of the glacial basin, and notes lithological differences between formations that may contribute to the presence (or absence) of groundwater. Chapter Three contains the results of the three geophysical surveys conducted during the course of this study and suggests the large and small scale structures that may be present within the Tekapo sub-basin. Chapter Four presents the water chemistry data and analysis. Chapter Five discusses the results of the age analysis of water samples collected and the possible recharge sources that may be present. Chapter Six summarises the springs located during the study and surface water/groundwater interaction that may be occurring within the sub-basins. Chapter Seven combines past and present data to suggest a groundwater regime that may be present within the Mackenzie Basin, and this is presented in the form of a conceptual hydrogeological model. Chapter Eight summarises all data and interpretations discussed within the preceding chapters, and makes recommendations for future investigations.

CHAPTER 2

GEOLOGY AND GEOMORPHOLOGY

2.1 INTRODUCTION

The geology of the study area in the Mackenzie Basin is based on mapping from various sources and primarily from the recently completed QMap of the Aoraki area by Cox & Barrell (2007). Details of the geological units at depth are based on information collated from drill holes, test pits, and shafts logged during the canal construction period from 1935 to 1985. The stratigraphy of the study area within the Mackenzie Basin is summarised, with the main emphasis on the glacial formations and alluvial deposits which form the lithological constraints on the presence of groundwater. The complex nature of the glacial basin is discussed in terms of both the geomorphology and the buried structures at depth.

2.2 REGIONAL SETTING

The Mackenzie Basin is located within the basins and ranges of South Canterbury which were formed by Late Cenozoic folds and faults striking northeast to north-northwest. The basins are situated within the synclines and the ranges are either anticlinal ridges or homoclinal fault blocks (Barrell & Cox, 2003). The tectonic depression of the Mackenzie Basin is the most westward of the basins which formed over the last 13 million years (Blick *et al.*, 1989). The ranges to the east are formed from Torlesse Greywacke, and Haast Schist of low metamorphic grade is present in the ranges to the west. Within the basin, basement rock of the Torlesse Supergroup also outcrops in the centre with inliers such as the Mary Range, rising to an elevation of approximately 1,000 m above sea level (MacFarlane, 1981).

Subsequently, the basin has been infilled with detritus deposited during the period of tectonic activity (Glentanner Formation), followed by multiple glacial events. The major glacial formations identified during geological mapping by Gair (1967) are: Birch Hill, Tekapo, Mt John, Balmoral I, Balmoral II, and Wolds. Following the retreat of the last glacial advance, post glacial alluvium covers much of the glacial deposits. The depth of the alluvial fill has been suggested to range from 300 m to 1000 m (Oborn, 1978), however, more recent large scale geophysical work suggests that in the centre of the Basin this could be closer to 2000 m (Long *et al.*, 2003).

2.3 STRATIGRAPHY

A geological map for the study area within the Mackenzie Basin is contained in Figure 2.1 (back pocket). Not all formations listed in the following text outcrop at the surface, and these are therefore not shown on the geological map. A stratigraphic column has been compiled from various sources that relate directly to the Mackenzie Basin area (Figure 2.2). The presence and thicknesses of formations at depth is highly variable, and defining the extent of buried moraines and other glacial features is difficult. A description of each formation is contained in Appendix 2A and is also briefly summarised below.

2.3.1 Basement Rocks

The basement consists of Torlesse Supergroup, and outcrops in the ranges surrounding and within the Mackenzie Basin. The Torlesse Terrane is predominantly a very well indurated, unweathered, greywacke and in places is interbedded with argillite. The upper part of the bedrock is weathered, jointed and fractured. The bedrock is impermeable to groundwater flows overall, however the fractures in the upper parts of the unit provide areas for rainfall to infiltrate leading to bedrock springs which can be seen throughout the basin.

2.3.2 Tertiary Sedimentary Deposits

The Tertiary deposits within the study area include the Eyre Group, White Rock Coal Measures, and the Kowai Formation (locally known as the Glentanner Formation). The Eyre Group only outcrops in the Hakataramea Pass, and it is unclear as to the extent within the Mackenzie Basin. The White Rock Coal Measures do not outcrop within the basin and their presence has been inferred from the geology of the Cannington Basin to the east and from geophysical surveys conducted within the Mackenzie Basin.

The Glentanner Formation outcrops in both of the major fault zones within the basin, and forms the basis of the hydrogeological basement based on the formations compaction and lithology. The non-marine, sub-angular, blue brown-weathered greywacke conglomerate is interbedded with very compact sand, silts, and silty clays (Gair, 1967; Macfarlane, 1981; Fox, 1987; Cox & Barrell, 2007). The formation is relatively impermeable in situ (Macfarlane, 1981).

2.3.3 Quaternary Deposits

During the Waimean age an ice advance led to the deposition of the Wolds Formation, which is overlain by an Interglacial Unit. During the Otiran age three ice advances led to the deposition of the Balmoral, Mt John, and Tekapo Formations. These glacial deposits are overlain by the Post Glacial Alluvial Gravels.

2.3.3.1 Wolds Formation

The Wolds Formation is a brown, moderately to highly weathered sandy gravel forms. Rare, discontinuous lenses are present, and the voids between clasts are filled with silty clay. Age and weathering has produced a compact, low permeability, formation at depth.

2.3.3.2 Interglacial Unit

A thin (<4 m) light grey, sandy silt layer unconformably overlies the Glentanner and Wolds Formations. The unit was observed in the Twizel area, and its extent throughout the basin is unknown.

2.3.3.3 Balmoral Formation

The Balmoral Formation consists of both till and outwash gravels (Figure 2.3 and Figure 2.4). The moraine that bounds the three glacial lakes, is chaotic, poorly graded, and contains a high content of silts and clays. The outwash gravels are slight to moderately weathered sandy gravels with voids infilled with silt and clay. The Balmoral Formation has a higher fines content than the overlying units and is therefore less permeable. The outwash gravels do have rare layers of well sorted gravels providing a limited amount of groundwater flow paths.

2.3.3.4 Mt John Formation

The till of the Mt John Formation is a poorly sorted gravely sandy silt, but occasional lenses of sandy gravel have been observed. The outwash gravels are well graded, fine to coarse gravel with some sand. Subhorizontal bedding, cross bedded infilled channels, well sorted openwork gravel layers, and sand lenses are common within the outwash gravels (Figure 2.5 and Figure 2.6). Silts and clays are common at the base of the openwork layers, due to percolating groundwater (Macfarlane, 1995). Channel structures are common and can be seen within the terraces along the Pukaki River. It is unknown whether the channel structures are continuous or interconnected. As the fines content of the Mt John outwash gravels is less than the underlying glacial formations and due to the layers and lenses of openwork gravels and sands, groundwater is thought to preferentially flow through the outwash gravels.

2.3.3.5 Tekapo Formation

The Tekapo Advance was a minor event closely following the retreat of the Mt John Advance (Mansergh, 1973). The Tekapo outwash gravels are generally unweathered sandy gravels with rare silt. The gravels form a thin surface veneer up to 5 m thick (Figure 2.7) (Read, 1976; Macfarlane, 1995). The silt and clay content is less within this formation compared to the Mt John Formation, but in every other respect the two formations are very similar and hard to differentiate. The outwash surfaces have many well defined, abandoned, braided channels, and this complex system can be seen on the surface as a braided drainage pattern. As the Tekapo and Mt John Formations have very similar lithologies groundwater is able to infiltrate downwards into the thicker Mt John outwash gravels.

2.3.4 Post Glacial Alluvial Gravels

The Post Glacial Alluvial Gravels are unweathered, sandy gravels with lenses of well sorted gravels and sands. The gravels occur predominantly within and around the present day river systems. It has been observed that the lower gravels have a higher silt content and therefore may provide a barrier to downwards infiltration of shallow groundwater (Read, 1974).

2.4 DEPTH TO BASEMENT

Speight (1961) describes the basement landscape as a complex of tilted tectonic blocks bounded by faults. The steep eastern slopes and gentle western slopes of all the ranges within the Mackenzie Basin are suggested to represent a pattern of faults and back slopes striking approximately north (Speight, 1961). Movement on these faults has resulted in the formation of a large, irregular rock rimmed basin elongated on a north east axis. The result of both tectonic activity and glacial activity is variable basement topography with the depth to basement estimated by Oborn (1978) to range from 300 m to 1000 m. More recent, large scale, geophysical surveys suggest the basement is closer to 2000 m at its deepest point (Long *et al.*, 2003). The results of the gravity survey undertaken as part of this study within the Tekapo sub-basin suggests a bedrock high within the centre of the sub-basin, under the Tekapo River (Figure 2.8)

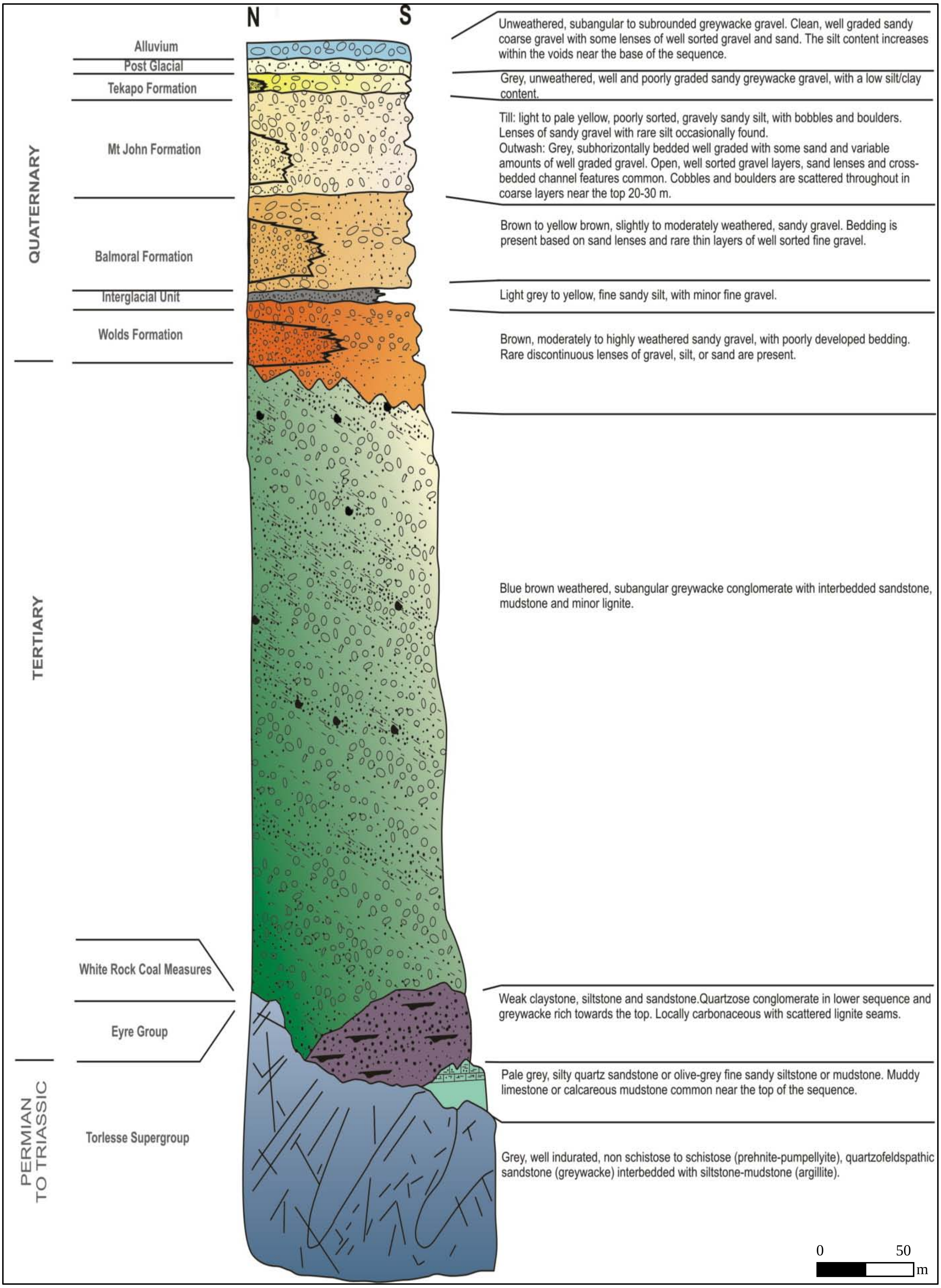


Figure 2.2: Stratigraphic column for the study area within the Mackenzie Basin, based on information compiled from various sources (Read, 1976; Macfarlane, 1981; Macfarlane, 1995; Chetwin, 1998; Cox & Barrel, 2007). The thicknesses are minimums only and not all formations are present in all areas. Some formation thicknesses are based on correlations with the nearby Cannington Basin to the east, and other formation thicknesses and presence are based on geophysical survey results only.

Figure 2.3: Balmoral Till overlain by Mt John Outwash Gravels. View is to the east (Grid ref: 2283104 5663018).

Figure 2.4: Balmoral Outwash Gravels overlain by Mt John Outwash Gravels. Note channel structures evident within the Mt John Outwash Gravels. The thin veneer of the Tekapo Outwash Gravels can be seen also. Terrace is ~30 m high. View is to the west. (Grid ref: 2284980 5660167).

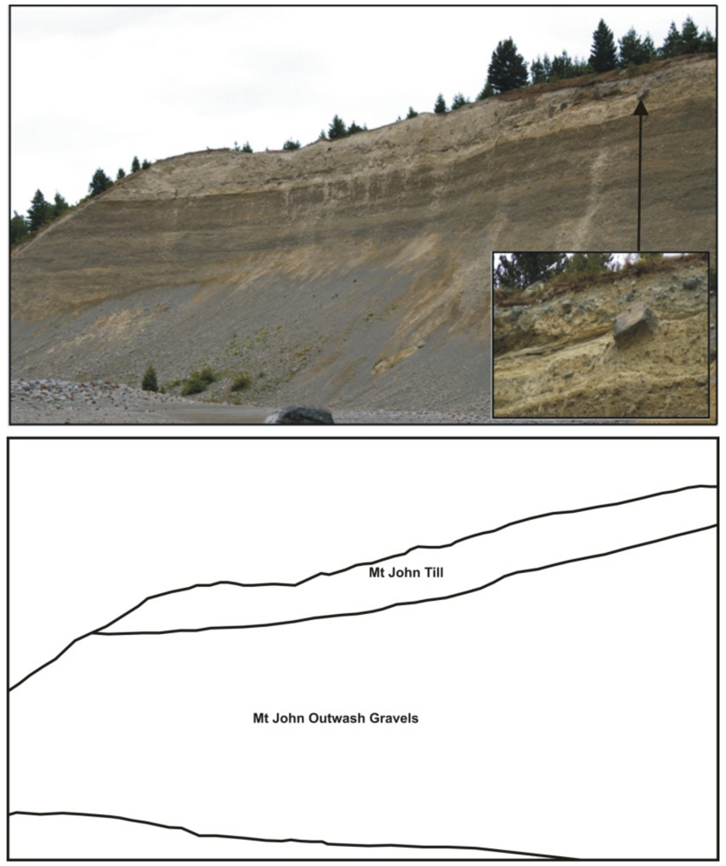


Figure 2.5: Mt John Till overlying the Mt John Outwash Gravels. Terrace is ~50 metres high. View looking north east. (Inset: close up of the Mt John Till) (Grid ref: 2283104 5663018).

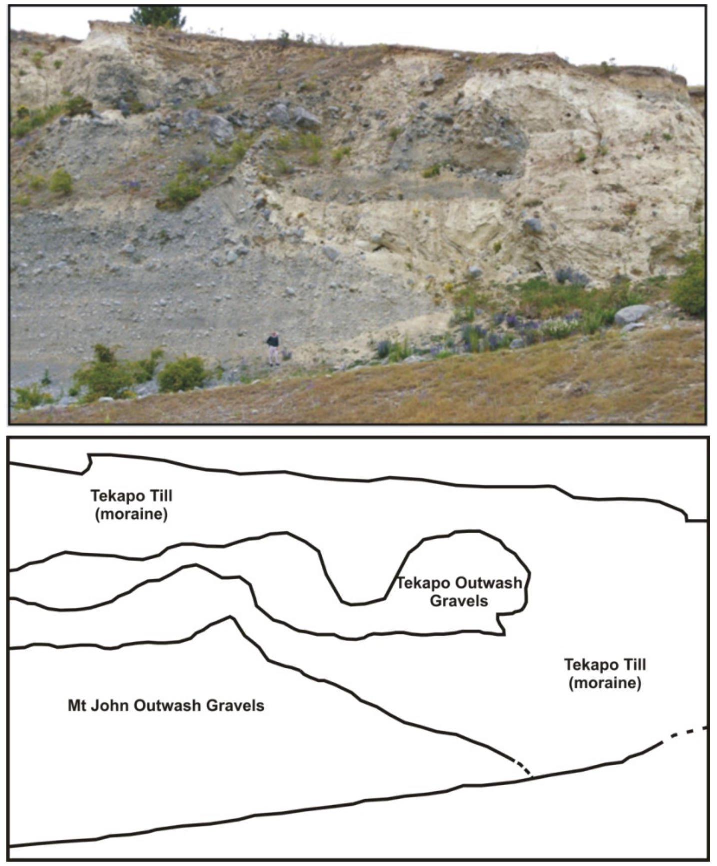


Figure 2.6: Tekapo Till that been thrust over the Mt John Outwash Gravels. Person for scale. View is to the west.
(Grid ref: 2281851 5664564).

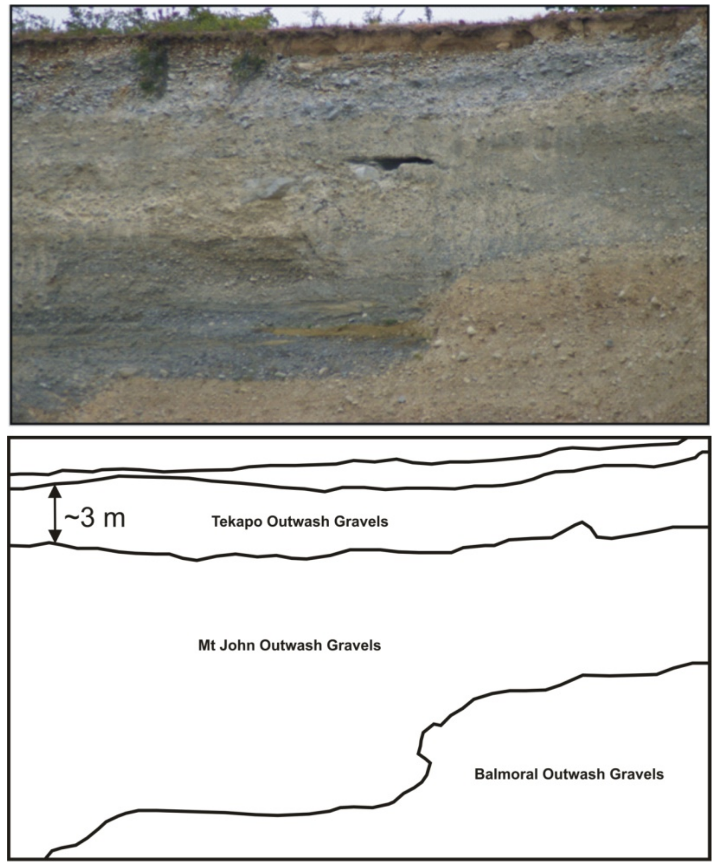


Figure 2.7: The layer of Tekapo Outwash Gravels overlies the Mt John and Balmoral Outwash Gravels. View is to the west. (Grid ref: 2284980 5660167).

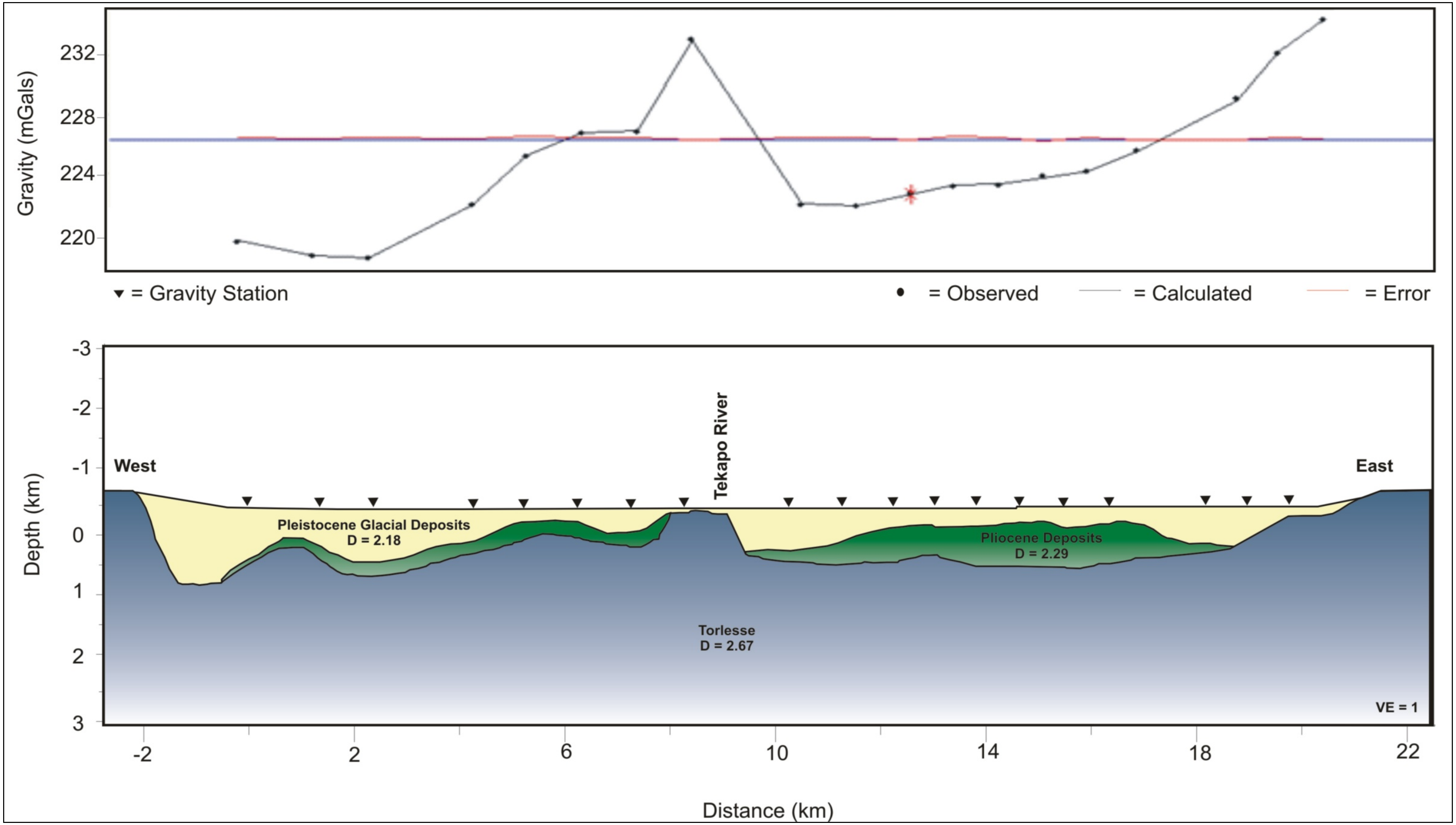


Figure 2.8: Gravity model indicating depth to basement. The model suggests that the Tekapo sub-basin is subdivided at depth into a further two sub-basins by the bedrock high beneath the Tekapo River.

2.5 GEOMORPHOLOGY

2.5.1 Geomorphic Surfaces

The Mackenzie Basin has a glacially dominated topography, with moraine loops and outwash plains associated with the major ice advances covering the majority of the area. Other glacial features that are also present include varves, kettle holes, kame terraces, lateral moraines, drumlins, flutes, and roche moutoneés. Aggradation surfaces extended from the terminal moraines as water flowing from the glacier front moved eroded material to the south. As the glaciers retreated, downcutting occurred creating terraces within the outwash gravels (Suggate, 1984).

The geomorphic surfaces were originally defined by Speight (1963) in the area surrounding Lake Pukaki. The 'landform associations' were named Pukaki, Maryburn, Irishman, and Stevenson, from youngest to oldest. In the area to the south of Lake Tekapo Maizels (1989) also reviewed the geomorphic surfaces in an attempt to constrain the ages of the glacial advances. The surface names used were Tekapo, Mt John, Balmoral, Wolds and Patterson Terrace, from youngest to oldest. The surface names defined by Maizels (1989) have been used to identify the alluvial outwash surfaces considered within this study.

The designation of the geomorphic surfaces by Speight (1963) was based on the freshness of the landforms and topographic detail, the amount of soil and silt cover, and the degree of weathering. Maizels (1989) used the morphological relationships, changes in elevation between terraces, loess cover thickness, development of surface drainage network, and the specific gravity of outwash clasts to define the surface origin (Figure 2.9).

The older outwash surfaces were found to be at a higher elevation to younger ones, and the thickness of the loess cover was significantly thinner on the Wolds and Balmoral surfaces than the cover on Patterson Terrace, and the Mt John and Tekapo outwash surfaces had even less cover than the older surfaces. The drainage patterns of the older, Wolds and Balmoral outwash surfaces are less distinct than the younger surfaces.

The Balmoral is distinctive from the Wolds, however, as dendritic networks have evolved creating a small number of bifurcating channels (Maizels, 1989). The Mt John outwash surface has an extensive, complex, highly braided paleochannel network with a high number of channel junctions and bifurcations (Maizels, 1989). The Tekapo and Mt John outwash surfaces are distinguishable from older surfaces as they tend to be stonier and have more well defined, abandoned braided channels (Oborn, 1978). The major rivers that drain the basin are all incised into the glacial outwash surfaces. The present day alluvial gravels are all degradational surfaces. The geomorphic features at the surface give an indication of the complex system that is present at depth. Older outwash surfaces have been reworked, re-deposited, and buried by subsequent glacial advances and retreats. The complexity of the abandoned braided channel systems is also evident within the Twizel sub-basin, and this is illustrated in Figure 2.10.

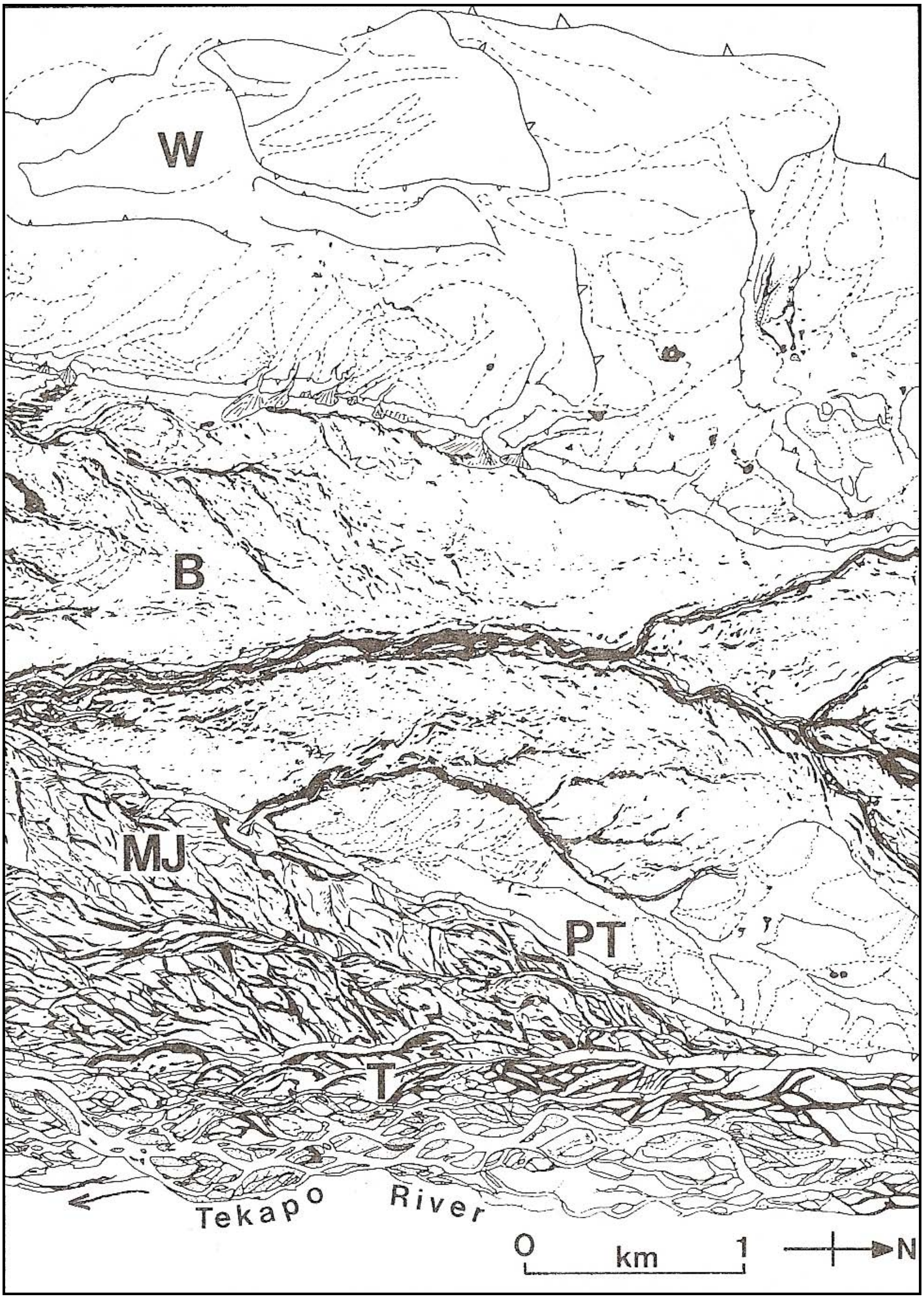
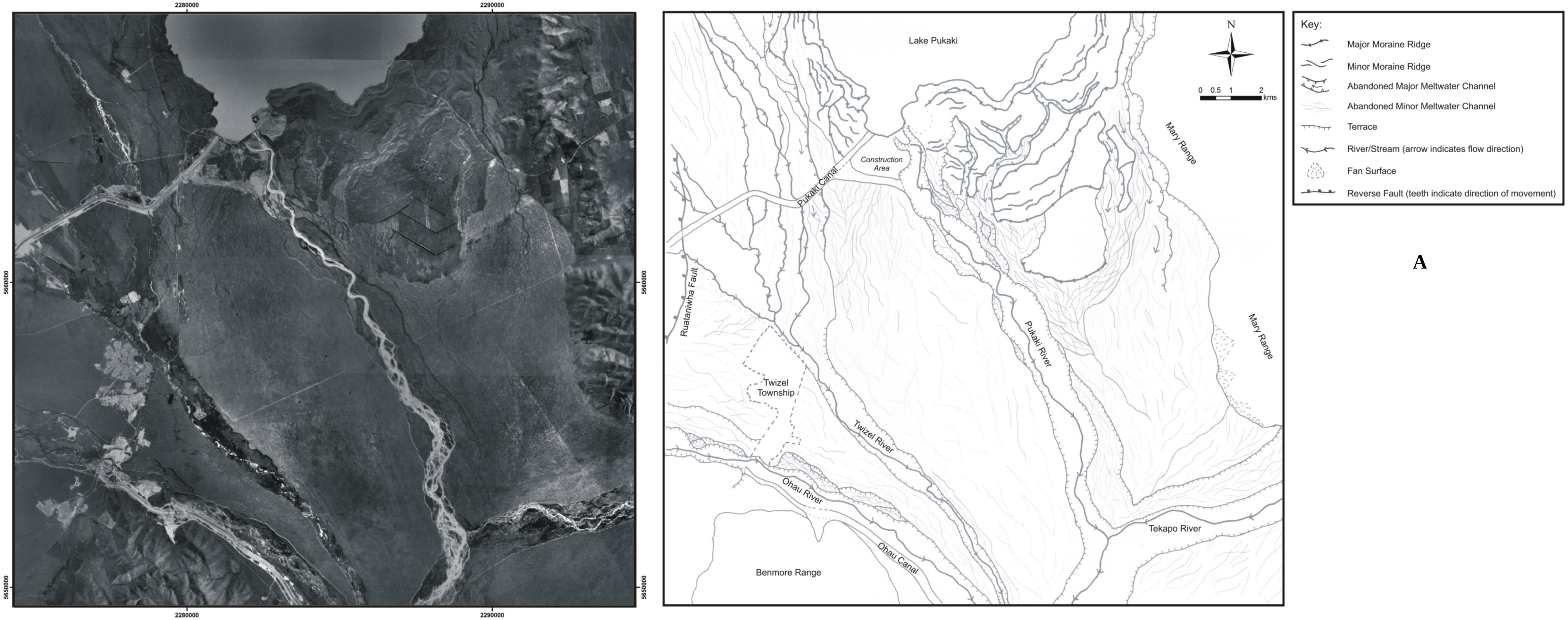


Figure 2.9: Paleochannel systems on the outwash surfaces west of the Tekapo River and south of Fork Stream. W = Wolds Formation, PT = Patterson Terrace; B = Balmoral Formation; MJ = Mt John Formation (Maizels, 1989).



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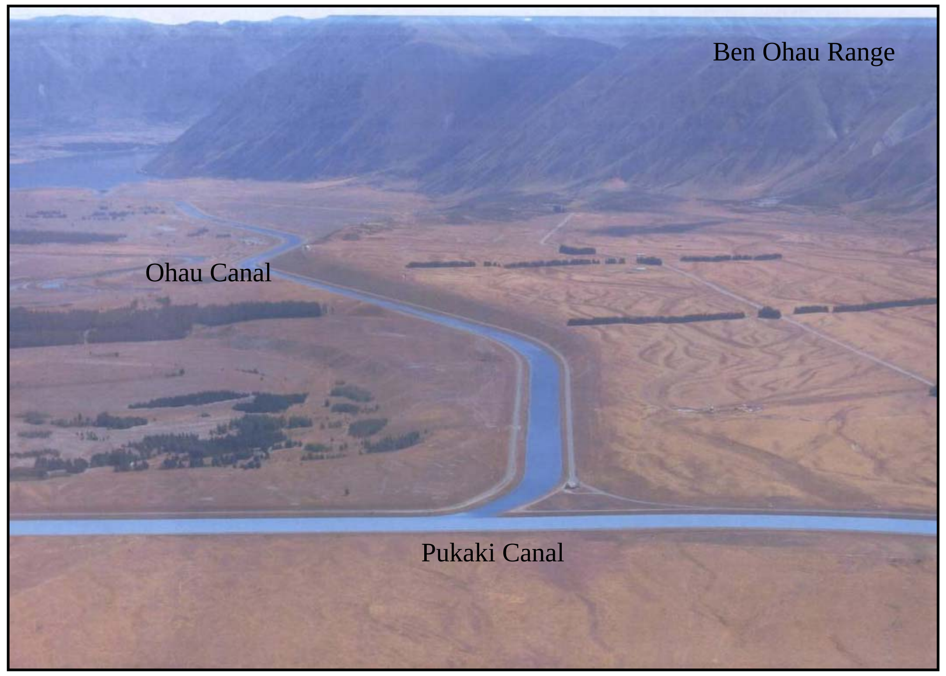


B

C

Figure 2.10: The complex glacial nature of the Mackenzie Basin is demonstrated on the surface of the glacial moraines and outwash surfaces.

A: Braided abandoned glacial outwash channels can be seen clearly in the area to the south of Lake Pukaki. The aerial photo was taken during the 1960's prior to the construction of the Ruataniwha Dam and the filling of Lake Ruataniwha (*photo: LINZ).*

B: Oblique aerial photo looking west towards Lake Ohau. The junction of the Ohau and Pukaki Canal system is in the centre of the photo. Deep abandoned outwash channels can be seen in the area between the Ohau Canal and the Ben Ohau Range.

C: Aerial photo of the Ruataniwha Dam shortly after Lake Ruataniwha was filled. The abandoned channels/drainage system can be clearly seen on the terraces on the north side of the Ohau River (*photo: Macfarlane, 1995).*

2.6 STRUCTURAL INFLUENCES ON THE HYDROGEOLOGIC SYSTEM

There are a number of structural influences that impact on the flow of groundwater within the subsurface. As the water bearing gravels are contained within an elongate basin, groundwater flow has a southerly direction towards Lake Benmore. The bedrock of the surrounding ranges, to the east and west, provide an impermeable barrier to groundwater flow. The topographic elevation also decreases from the northwest to the southeast, and bedrock topography at depth is likely to follow this pattern. The inliers of bedrock within the centre of the basin (Mary Range, House Hill, and Grays Hills), further subdivide the groundwater flow into two separate major sub-basins. These have been designated as the Tekapo sub-basin and the Twizel sub-basin for the purposes of groundwater flow analysis within this study. The two sub-basins share a hydraulic link via the Tekapo River. The bedrock highs in the centre of the basin bring groundwater flows towards the surface and this is seen where swamp areas are present at the base of the ranges. Grays Hills has a significant impact on groundwater flowing at depth from the north, which is brought to the surface, evidenced by a large number of springs and swamps. The water then flows towards the Tekapo River to the west.

The other major structural influences that are likely to impact on groundwater flow are the two major fault systems within the basin; the Irishman Creek Fault and the Ostler Fault Zone (Figure 2.11). Faults have brought the much lower permeability Glentanner Formation to the surface in the foot wall of both of the major fault systems. Springs and an accumulation of water at the base of both of the fault trace outcrops were observed, which is likely to be from both groundwater and surface water flows being impeded by the lower permeability unit.

2.6.1 Irishman Creek Fault

The Irishman Creek Fault strikes northeast along the edge of the Old Man Range near Lake Tekapo. This segmented thrust fault has a surface expression which can be seen for approximately 11 km. The predicted depth of the fault is approximately 1.3 km, and has a suggested slip rate of the Irishman Creek Fault by of approximately 1.1 to 1.7 mm/yr based on luminescence dating (Amos *et al*., 2007). The faulting and back-tilting within the Irishman Creek Fault has affected the older surfaces more than the younger surfaces (Speight, 1963) (Figure 2.12). The Irishman Creek Fault and the Old Man Range has been incised by the Irishman Creek which flows from the north through the Irishman Creek Gorge, exposing the Glentanner Formation (Figure 2.13). The cut off, back tilted, drainage patterns of the Wolds outwash surface can be seen in Figure 2.12.

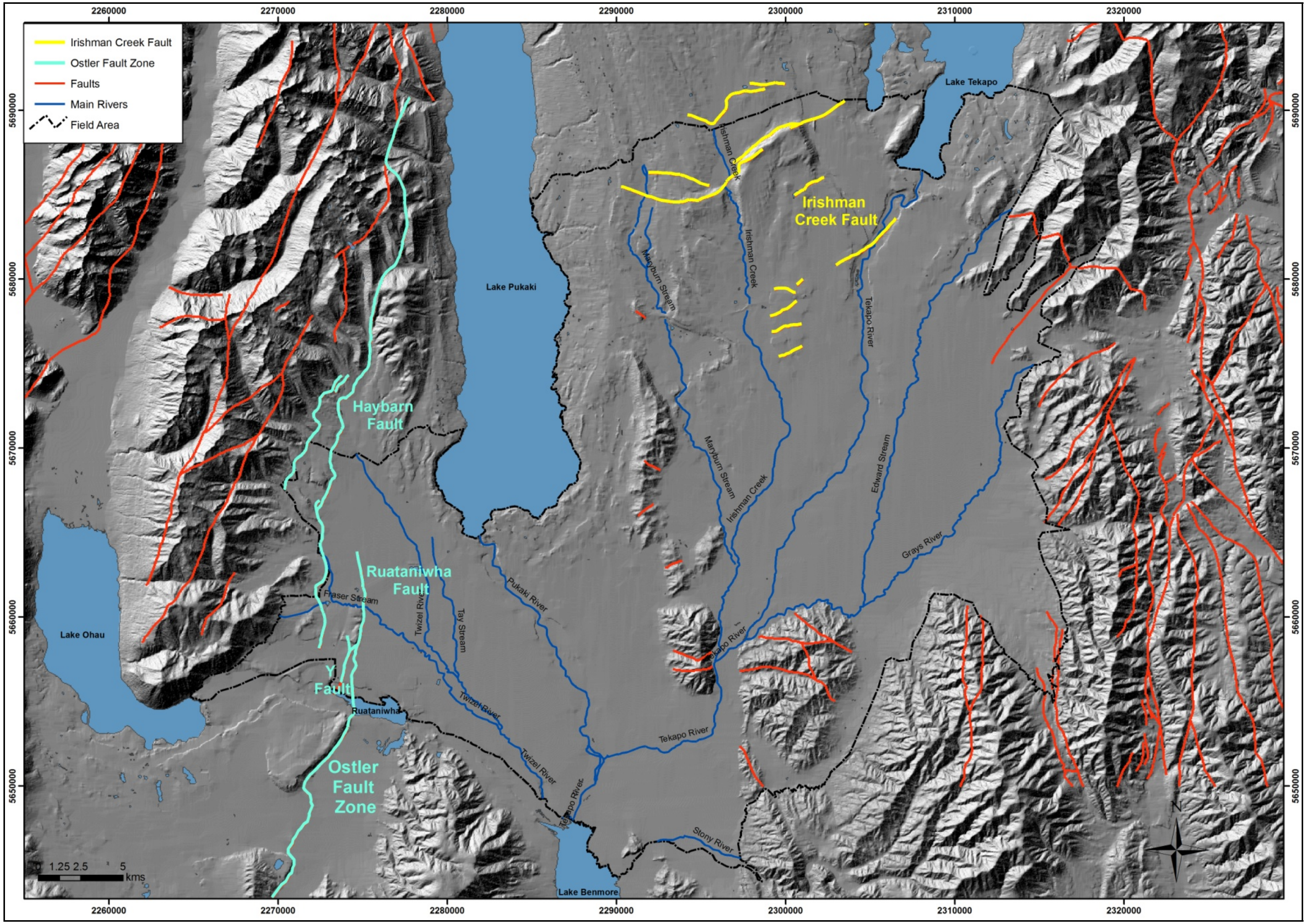


Figure 2.11: Location map of faults in the Mackenzie Basin and surrounding areas (digital geological data sourced from the Institute of Geological & Nuclear Sciences, 2008).

The Irishman Creek Fault has cut through the drainage system and springs and swamps were observed at the base of the fault trace outcrop. It is likely that both surface water and groundwater flows are impeded by the up-thrown, lower permeability Glentanner Formation, forcing water flows towards the Irishman Creek Gorge to continue southwards.

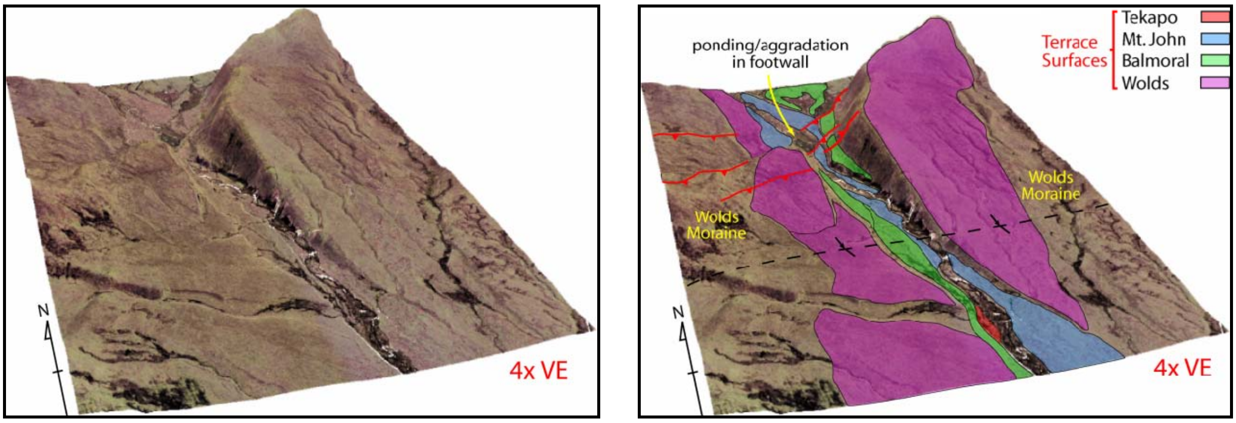


Figure 2.12: 3D perspective of the Irishman Creek Gorge. The older glacial formations (Wolds) are more affected by the back tilting than the younger formations (Mt John) (Amos *et al.*, 2007).

Figure 2.13: The Glentanner Formation is exposed on the up-thrown block of the Irishman Creek Fault. Length of outcrop is approximately 1500 metres. View is to the southwest (Grid ref: 2295670 5684957).

2.6.2 Ostler Fault Zone

The Ostler Fault Zone strikes north-northeast along the western side of the basin. The segmented thrust fault has an active fault trace up to 3 km wide that can be seen running for at least 50 km from Boundary Stream in the north to the Ahuriri River in the South (Read, 1984). The west side of the fault trace is up-thrown and back tilted, exposing the Glentanner Formation (Figure 2.14). The depth of the listric fault is predicted to be approximately 0.7 km, with a slip rate of the Ostler Fault to be approximately 0.5 to 0.7 mm/yr based on luminescence dating (Amos *et al.*, 2007). The glacial surfaces preserved along the Ohau River have a vertical displacement of 13 m to 15 m. The ratio of scarp heights to the displacement across the fault zone varies from 3:2 to 2:1 (Read, 1984). The back tilting of older surfaces (Wolds and Balmoral) can be seen in Figure 2.15. The displacement of the Glentanner Formation in an upwards direction produces a lower permeability barrier to groundwater flow, evidenced by ponding and springs at the base of the north side of the up-thrown fault block.

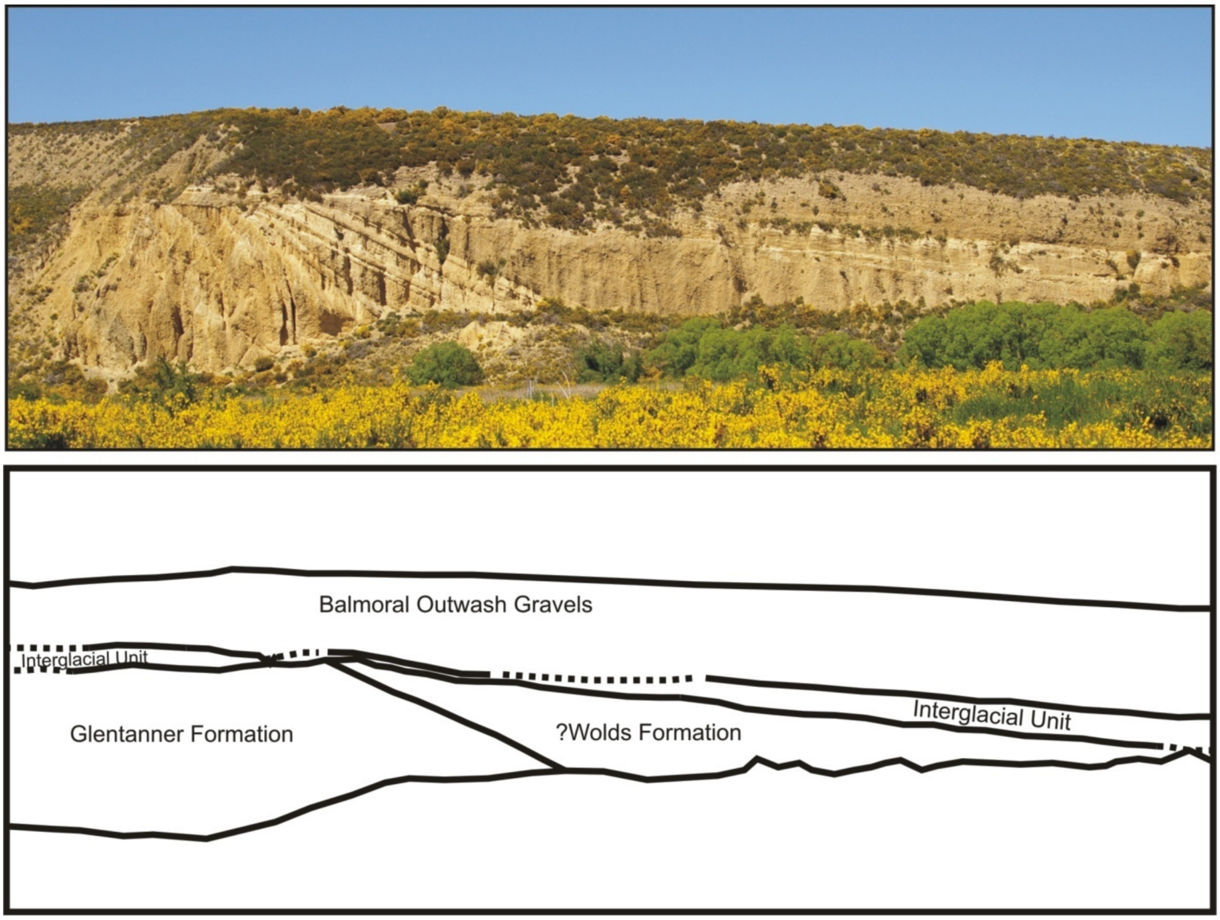


Figure 2.14: The Glentanner Formation and the two older glacial formations are exposed in the up-thrown block of the Ostler Fault Zone (Ruataniwha Fault), near the Fraser Stream in Twizel. View of outcrop is approximately 300 metres wide. View is to the south (Grid ref: 2274753 5660583).

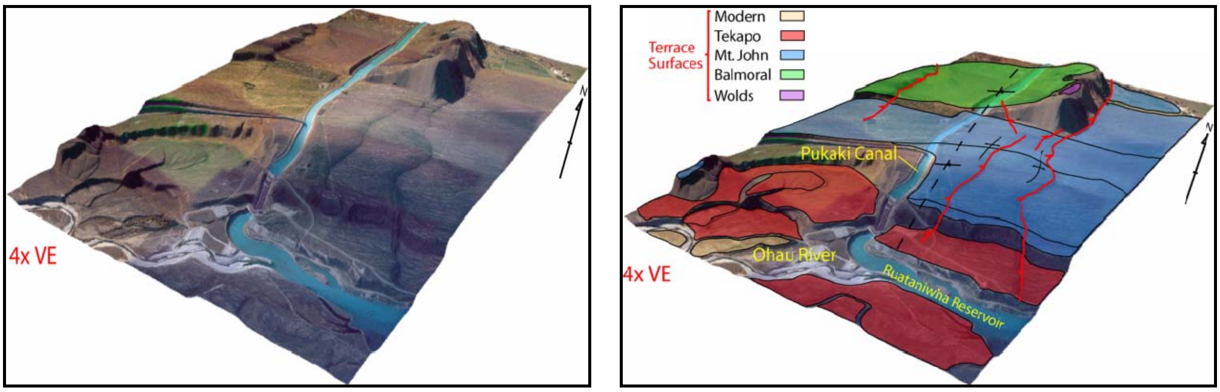


Figure 2.15: 3D image of the Ruataniwha Fault which forms part of the Ostler Fault Zone. The Balmoral surface can be seen on the back tilted footwall of the fault (Amos *et al.*, 2007).

2.7 DEPOSITIONAL AND GEOMORPHIC INFLUENCES

The Glentanner Formation is suggested to represent the 'hydrogeological basement' for the Mackenzie Basin. The age and compaction of the formation, combined with the interbedded layers of sand, silts and silty clays, suggests that it is a relatively impermeable unit in comparison to the overlying glacial formations. The older glacial formations (Wolds and Balmoral) are also likely to have a reduced permeability in comparison to the Tekapo and Mt

John Formations due to their age and compaction at depth. In comparison, the Tekapo and Mt John Outwash Gravels contain cleaner gravels with buried openwork channels and lenses of gravels and sands, providing conduits for groundwater flow. The large fan surfaces that are mainly located on the ranges surrounding the basin provide another system for groundwater movement. The most extensive fans are located in the Mackenzie Pass and the Hakataramea Pass on the east side of the basin. The fans are composed mainly of post glacial gravels and eroded Torlesse Terrane.

2.7.1 Glacial Lakes

Within the Basin there are three glacial lakes which are impounded behind the terminal moraine of the Tekapo Advance. Each of the lakes was formed in the depression left by the retreating ice after the Tekapo Advance. The varved lake sediments at the bottom of the lakes are thought to be several hundred metres thick, containing silts and clays, therefore perching the lakes (Figure 2.16). The lake sediments within Lake Tekapo can be seen exposed on the south western shore. These indicate a seasonal fluctuation of sedimentation and show how fine and compact the sediment is. A faulted, layered lake sediment outcrop is shown in Figure 2.17. A seismic survey conducted across Lake Tekapo indicates fine grained sediment of varved silt and mud deposits to depths of up to 145 m below the lake floor (Upton & Osterberg, 2007).

2.7.2 Buried Glacial Features

Given the present limited availability of data from both bore logs and shallow geophysical surveys, it is difficult to determine the extent of buried glacial features at depth.

Although many glacial features (such as moraines, varves, and drumlins for example) will have been ‘overrun’ by retreating glaciers and then reworked by following glacial advances, it is possible that some may have been preserved and may form aquicludes or aquitards at depth. The seismic surveys across Lake Pukaki and Lake Tekapo indicate the possible existence of moraines at depth beneath both of the lakes (Carter & Carter, 1990; Upton & Osterberg, 2007).

Wherever terminal moraines are present it is likely that lake sediment deposits, similar to present day lake sediments, are present behind the moraine loop. When the ice has retreated a glacial lake will be formed that is impounded by the moraine ridge. Therefore very fine lake sediments similar to those in Figure 2.17 are likely to be buried at depth behind the moraines and will represent an aquitard lithology.

Fluvioglacial melt water channels will also be buried at depth, and like the present glacial outwash surfaces the paleochannels are likely to be highly complex and braided, and may provide interconnections for groundwater flow. However, previous reworking of these channels may cause the buried channels to be ‘cut off’ and localised pockets of silts and clays will be present in arbitrary locations both vertically and horizontally. The reworking of older outwash gravels forming buried channels is suggested as the model for the seismic refraction survey undertaken during this study within the Tekapo sub-basin (Figure 2.18). It is likely that this buried channel system is present throughout the Mackenzie Basin at depth.

Further influence on groundwater flows from glacial activity is provided by the compaction of older formations, such as the Wolds and Balmoral Outwash Gravels, which are much older than the other Quaternary deposits and have mostly been buried considerably by overlying formations. The compaction of these outwash gravels reduces the ability of the lithology to transmit groundwater therefore reducing the permeability of the glacial outwash gravels at depth.

The proximity of the outwash gravels to the terminal moraines also plays a part in the hydraulic conductivity of the formation. Outwash gravels that are proximal to the moraine ridge will be larger, more angular, but less sorted. The more distal from the moraine ridge produces smaller, more rounded, and more sorted outwash gravels, with a higher sand and silt content. The lack of sorting of the gravels close to the moraine results in a limited amount of pore space as well as low interconnectivity of the pore spaces and therefore lower permeabilities compared to outwash gravels that are more distal.

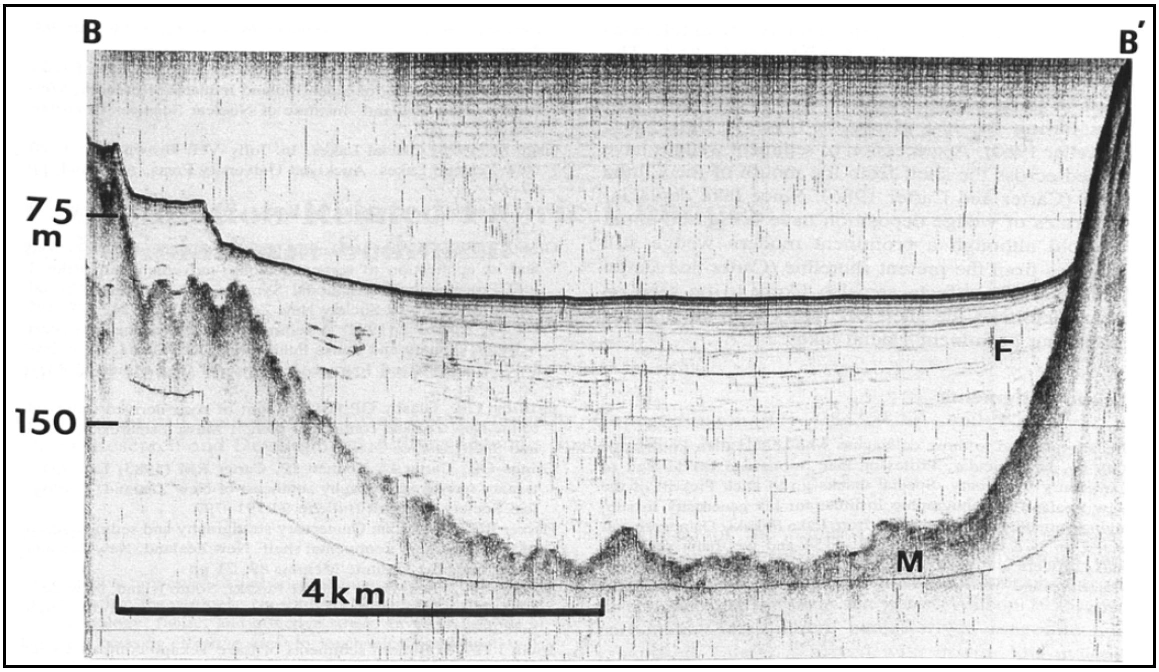
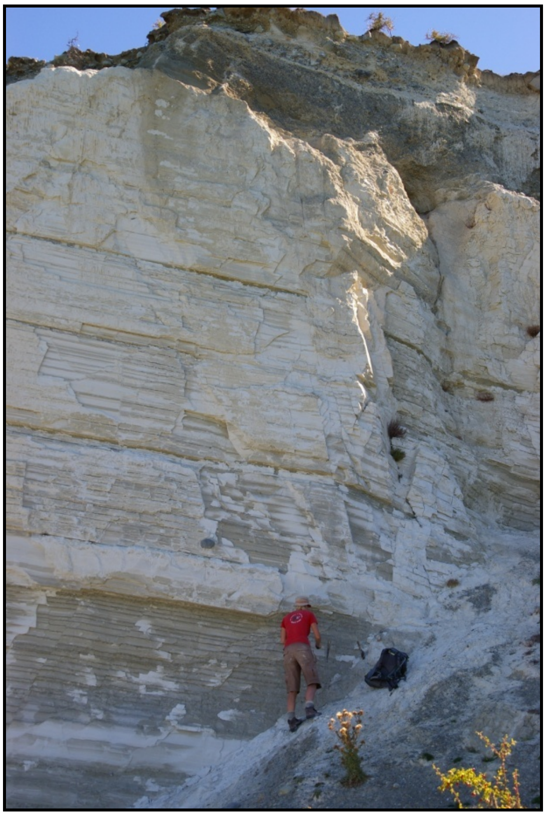


Figure 2.16: The depression left by the retreating glacier has created a 'sediment trap' creating the varved basin fill (F) of Lake Pukaki, which indicates a thick layer of sediment at the base of the lake possibly perching the water above. The cross section is a high resolution seismic profile running from southwest to northeast at the southern end of Lake Pukaki (Carter & Carter, 1990).



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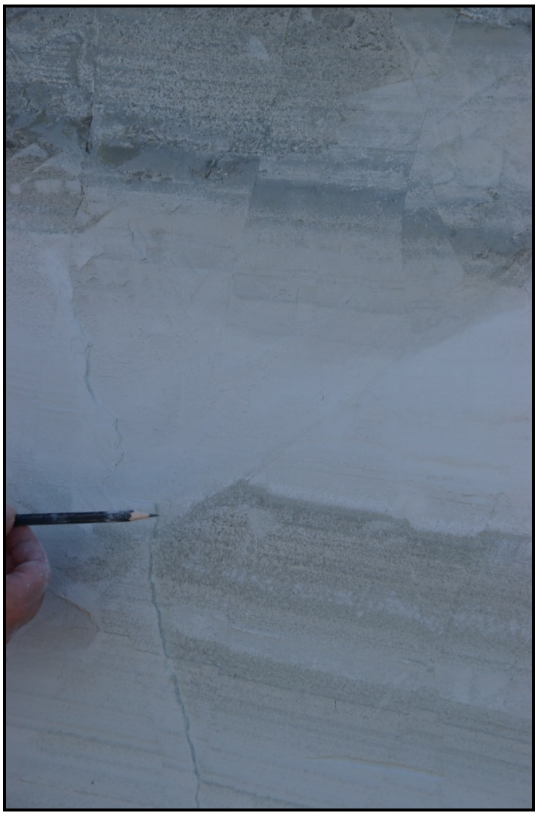


B

Figure 2.17: Exposed lake sediments on the south western shore of Lake Tekapo. A) The layering indicates possible seasonal fluctuations of sediment. B) The very fine silt and clay layers of the lake sediments are shown which are glacio-tectonically faulted.

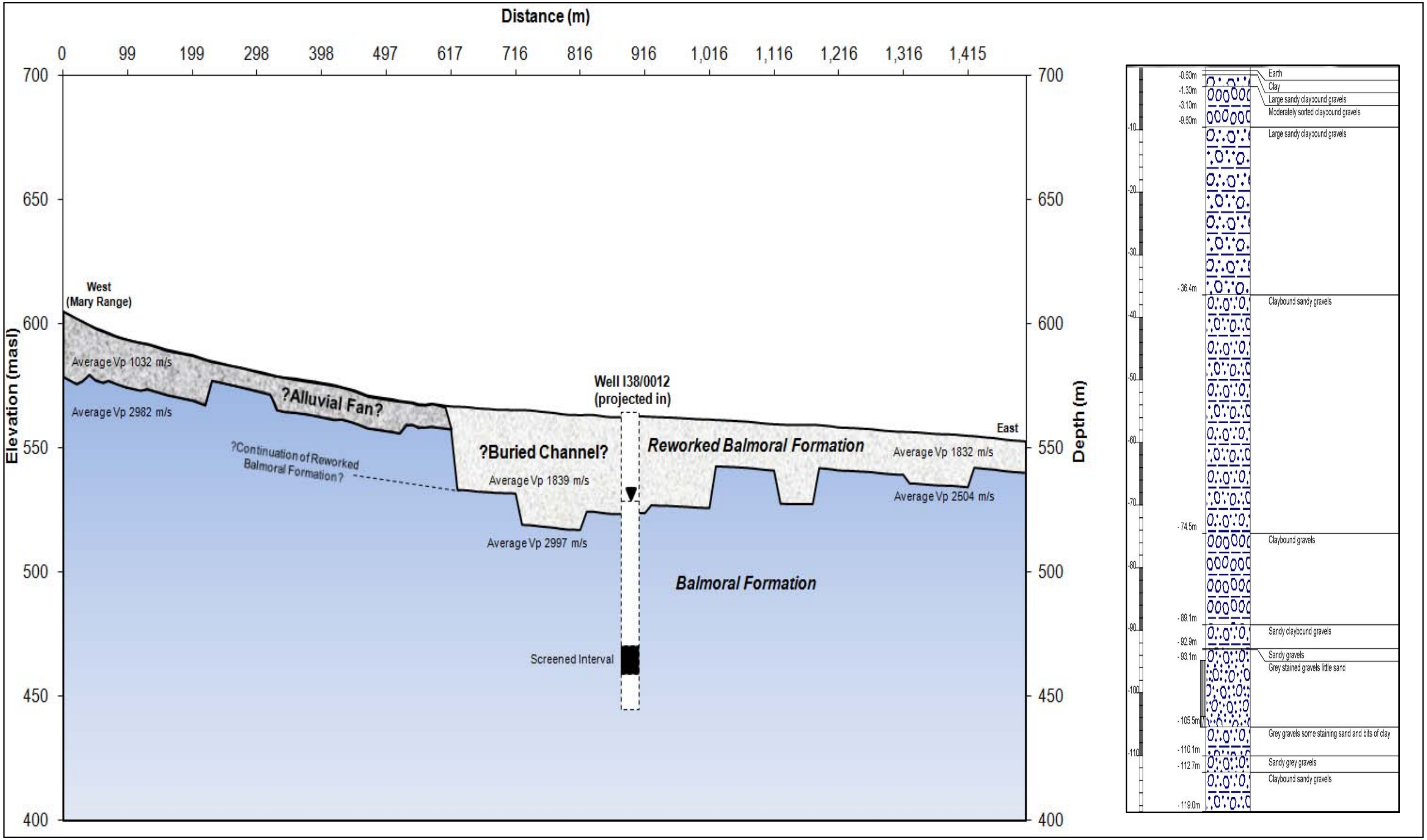


Figure 2.18: Two layer seismic refraction model. Average velocities of each layer are noted to indicate the changing velocities from west to east. The bore log for well I38/0012 has been projected back into the line (its actual location is ~600m to the south of the survey line). Buried channels of reworked outwash gravels are present close to the surface.

2.8 CHAPTER SUMMARY

The Rakaia subterrane metamorphically grades towards the west to form part of the Haast Schist. In the Miocene the Alpine Fault was formed by tectonic plate movements, leading to uplift close to the continental boundary and subsidence towards the east coast. The continued uplift of the Southern Alps led to erosion and provided greywacke and schist sourced sediments for accumulation in the Pliocene and Quaternary. During the Kaikoura Orogengy folding and faulting created the Canterbury basins and ranges. During this period downwarping formed a depression which is now the Mackenzie Basin. The Glentanner Formation was deposited during the Late Miocene to Early Quaternary, followed by glacial and interglacial periods. The Mackenzie Basin contains the deposits from four major ice advances; the Wolds, Balmoral, Mt John, and Tekapo (from oldest to youngest). The ages of the four formations range from >300 ka to ~16 ka, but there is much debate as to the actual ages of each formation.

The fractured Torlesse bedrock outcrops in the ranges surrounding the Mackenzie Basin and in the inliers at the centre of the basin. The depth to basement is estimated at around 2000 m at the centre. The structural highs of the bedrock and up-thrusting of the low permeability Glentanner Formation along the Ostler Fault and Irishman Creek Fault form impermeable boundaries to groundwater flow. This has restricted the groundwater to two major sub-basins; the Tekapo and Twizel sub-basins.

The compaction and lithology of the Glentanner Formation provides the basis for the hydrogeological basement due to the formation’s low permeability. The older glacial formations such as the Wolds and Balmoral are suggested to be less permeable than the younger, overlying formations (Mt John and Tekapo). Permeability reduces with depth and with proximity to glacial moraines. The lithological complexity of the formations at depth is difficult to define and is complex due to the processes of advancing and retreating glaciers. The reworking of deposits by multiple glaciations creates discrete channels, buried glacial features, and isolated lenses of silts and clays that are geologically heterogeneous and variable in thickness. The complexity of the glacial outwash gravels at depth is illustrated by the dissected, dendritic drainage pattern present on all of the outwash gravels at the surface. It is probable that the younger formations (Mt John and Tekapo), which are cleaner, more sorted, and have openwork gravel lenses, provide a suitable lithology for the presence of aquifers. The Post Glacial Alluvial Gravels and fan surfaces also have a lower silt and clay content and are likely to provide easy flow paths for groundwater.

CHAPTER 3

GEOPHYSICS

3.1 INTRODUCTION AND OBJECTIVES

During the course of this study three different geophysical techniques were used to investigate the subsurface geology and the occurrence of groundwater within the Mackenzie Basin. The three methods used were: gravity, time-domain electromagnetics (TEM), and seismic refraction and reflection. The primary purposes of the geophysical surveys carried out during this study were to define the hydrogeological basement, thicknesses of Quaternary formations, and to locate any water tables that may be present.

The gravity survey was used to estimate the depth to bedrock, and to define any bedrock topography that may be present at depth. The method could also be used to estimate the thickness of overlying gravel units. The TEM survey was conducted to identify changes in lithology at depth, and to identify any water bearing units that may be present. The seismic survey was carried out to define the stratigraphic detail closer to the surface, such as buried paleo-channels and changes in lithology.

Over the last four decades, numerous geophysical surveys have been conducted within the Mackenzie Basin. The initial purpose of the surveys was to define foundation conditions, geological boundaries, and the presence of groundwater for the purposes of canal and dam construction. More recently, the focus of research has been on the active fault zones within the area and large-scale structures such as basin structure and the effect of the Alpine Fault. Literature regarding these surveys has been reviewed and are summarised in Appendix 3A.

3.2 GRAVITY SURVEY

3.2.1 Background

In June 2007 a gravity survey was undertaken across the width of the Tekapo sub-basin. The purpose of the survey was to provide an indication of the depth to the Torlesse basement. The theory and methods of gravity surveying are discussed in detail in many texts such as Kearey & Brooks (1991); Parasnis (1986); and Milsom (2003).

Gravity surveying is used for subsurface geological investigations using variations in the Earth's gravitational field due to density differences between subsurface materials. Buried anomalies, such as buried valleys, can produce relief within the bedrock surface (Kearey & Brooks, 1991). The gravity survey theory has been summarised and is contained in Appendix 3B.

3.2.2 Field Methods

The gravity survey was conducted using a Worden Gravimeter from Otago University. The survey contained 22 gravity stations along a 22 km line running west to east near the centre of the Tekapo sub-basin (Figure 3.1). The survey line was chosen for ease of access using farm tracks, rather than for any specific geological reason. The survey spacings were approximately 1000 m apart to enable the distance to be covered in the time available.

The survey was divided into two parts, each of which was completed within one day. Each 'sub-survey' had a base station which was revisited after the measurement of two observation stations, when possible. The looping back to the base station enabled corrections to be made for variations in the Earth's gravity and the effects of instrument drift. Three readings were taken at each station, which were then averaged. The variations in readings, however, were more than 3 gu, rather than the recommended 0.3 gu due to user error, making the accuracy of the data questionable.

The location and elevation of the gravity stations were determined using a Trimble differential GPS receiver which has an accuracy of 10 cm horizontal and 20 cm vertical. During field data collection, environmental factors can also affect the quality of the data collected. These include wind, vehicle vibrations, and user capability. Wind was compensated for by shielding the gravimeter from the wind and moving large objects (such as vehicles) far enough away from the meter so that they had no effect. When collecting data near roads, readings were taken when no vehicles were present.

Background variations can affect gravity measurements and these need to be accounted for before the data can be interpreted correctly. Corrections need to be made for elevation, topography, solar and lunar tides, instrument drift, and latitude. The definition of each of the corrections required for gravity surveys is contained in Appendix 3B.

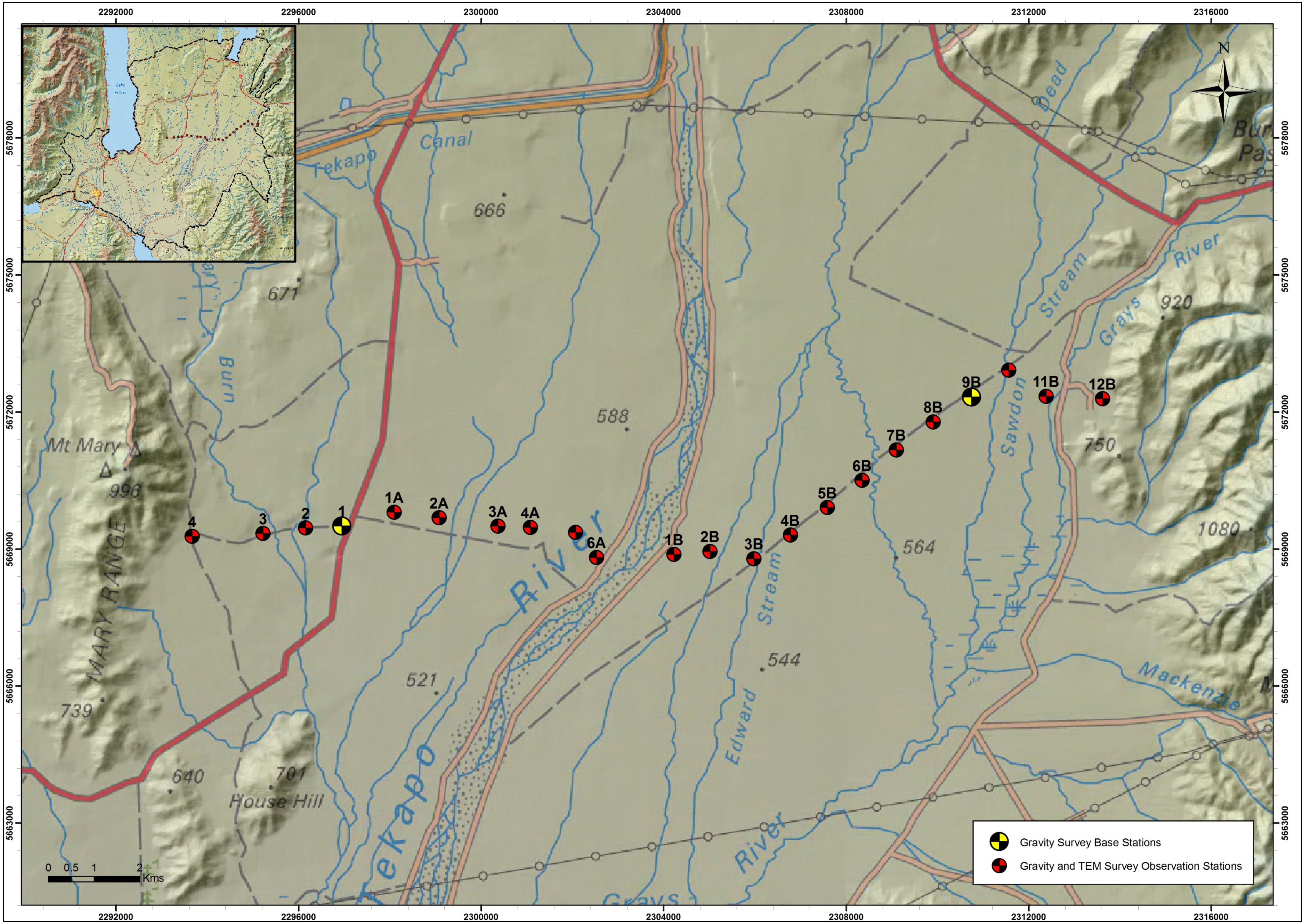


Figure 3.1: Location of gravity observation and base stations. The same locations were used for the TEM survey also. (Inset: location of survey line within the field area).

3.2.3 Gravity Results

3.2.3.1 Data and Corrections

The raw and corrected data are contained in Appendix 3C. The corrected data results in an anomaly of 15 mGals with a standard deviation of approximately 0.2 mGals. To correct for temporal variation in the background gravitational field during the survey, multiple revisits to the base station were undertaken to remove this variation. The base station for each group of observation stations were to be re-measured approximately every hour, but due to time constraints and distance between stations this was not always achieved. This has created issues of accuracy when reducing the raw data. The variation of the base station was approximately 1 mGal over a period of one day. The gravity anomaly is fairly low, therefore, not greatly affecting the results. It is also assumed that the survey line was straight to create a 2D model. The stations have been interpolated back to a straight line to create a 2D model. This means that the model does not take into account changes in basement topography in three dimensions.

3.2.3.2 Rock Densities

It is necessary to define rock densities for both Bouguer corrections and interpretation of the data. Because gravity anomalies result from the difference in density (ρ) between a rock and its surroundings, it is necessary to determine density contrasts using $\Delta\rho = \rho_1 - \rho_2$.

The densities of rocks are a result of composition and porosity. Generally the density of sedimentary rocks will increase with depth due to compaction and cementation (Kearey & Brooks, 1991). Often a density of 2.67 Mg m^{-3} is used for the density of the upper crust when modelling gravity data (Milsom, 2003). Density ranges of some common materials are included in Table 3.1.

Table 3.1: Density ranges (adapted from Parasnis, 1986; Kearey & Brooks, 1991).

Density ranges of some common materials (Mg m^{-3})	
Oil	0.90
Water	1.00
Coal	1.20 – 1.50
Sand, dry	1.40 – 1.65
Clay	1.63 – 2.60
Sandstone	1.80 – 2.70
Sand, wet	1.95 – 2.05
Alluvium (wet)	1.96 – 2.00
Shale	2.06 – 2.66
Granite	2.50 – 2.70
Limestone	2.60 – 2.80
Gneiss	2.61 – 2.99
Basalt	2.70 – 3.30

Density (ρ) needs to be determined for each layer in a gravity model to eliminate the effect of surface features. Parasnis (1986) notes that it is possible to determine the densities using laboratory measurements of samples; however, samples can be affected by weathering and may not be representative of rocks at depth, especially in areas of moraine and clays. Nettleton's method can be used to determine the density of rocks, which involves taking gravity observations over a small area with topographic highs. The data is then reduced using different densities in the terrain and Bouguer corrections. The density value that creates a Bouguer anomaly with the least correlation with topography is used as the representative density for the area. Density can also be determined from the P-wave velocities of rocks from seismic surveys (Kearey & Brooks, 1991). The density values used for this study are based on data from Chetwin (1998) and Kleffman (1999), who both carried out gravity and seismic surveys within the Mackenzie Basin.

3.2.4 Gravity Interpretation

The main problem with gravity surveys is the non-uniqueness of data. Multiple models can be created which will fit the same set of data, and therefore a method of ground-truthing the data is needed. In this particular case, the 'most likely' model is illustrated in Figure 3.2. Alternative models that also fit this data are contained in Appendix 3D. Although the chosen model appears to fit the observed gravity data very well, it is very difficult to define the thicknesses of the overlying Pliocene and Pleistocene gravel deposits. For example, by altering the density values of the gravels leads to a change in thickness of the gravels, creating an alternate model that still fits the data. The current model indicates that the total thickness of the overlying gravels is in the range of 1000 m. Although it is difficult to quantify the thickness of the gravels, it can be noted that they are very thick within this part of the basin. There is distinct bedrock topography and this topography remains fairly constant in all three models that have been derived. The bedrock high, underlying the Tekapo River, creates two buried sub-basins within the Tekapo sub-basin. The topography of the bedrock is similar to that found further to the north of this survey line, during a gravity and seismic survey undertaken by Kleffman (1999). Other gravity models were created to determine the effect if the bedrock high was removed from the model. The data did not fit this model nearly as well as the current model in Figure 3.2, suggesting that the bedrock high is likely to exist. However, the bedrock high is based on data from one gravity station and therefore another gravity survey with a smaller station spacing should be conducted to confirm the bedrock topography.

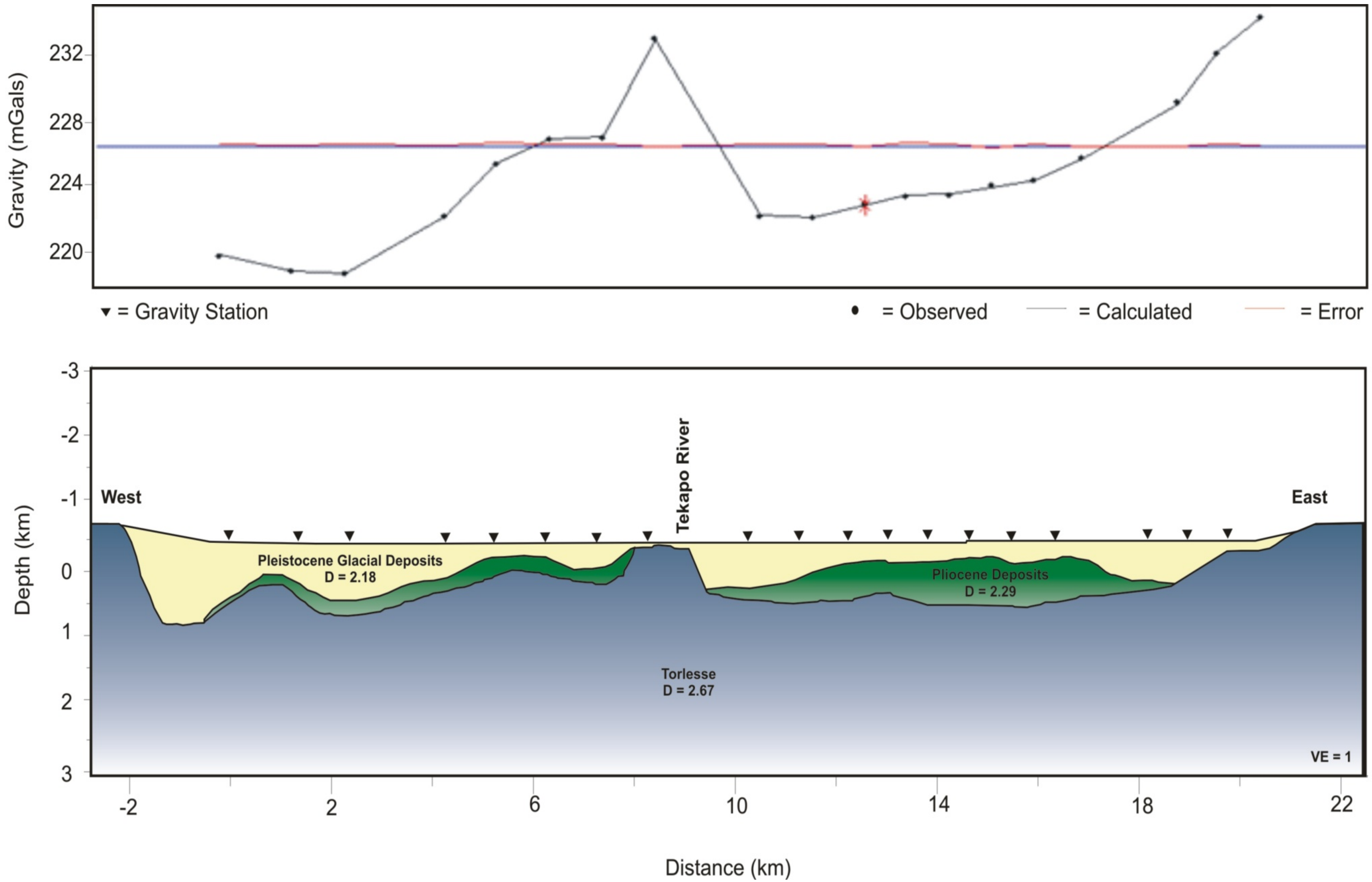


Figure 3.2: One of a number of gravity models created for the gravity data collected from the survey done across the Tekapo sub-basin. The model indicates that there is likely to be approximately 1000 m of Pleistocene and Plicocene gravels overlying the Torlesse bedrock. The bedrock high cuts the sub-basin into two further sub-basins at depth. The forward model indicating how the model correlates with observed data is shown above the model.

3.3 TEM SURVEY

3.3.1 TEM Theory

In TEM surveys a signal is created by a transmitter loop creating induced currents. A ground response builds to a maximum when the transmitter is switched on. The transmitter is then turned off quickly which turns off the magnetic field quickly. The rapid change from on to off induces a voltage in the ground, which in turn induces an electric current to flow in the ground. This induced current creates a secondary magnetic field. The response to this secondary field decays over a period of time which is dependent on the electrical properties of the ground. The response is measured over a number of time intervals and channels which form a time window. The signal will decrease exponentially with time if the electrical properties of the ground are uniform. Measuring the rate of signal decay indicates the electrical properties of the ground as a function of depth. In both early and late times the signal will be weak, therefore measurement is carried out within specific time periods. The channels are spaced logarithmically, and the time channels increase in duration so that more signal can be used during measurement as the signal strength decreases.

Figure 3.3 illustrates the flow of the eddy current in both early and late time periods. The centre of the ring of current moves out and down as the current moves out and its strength decreases (Nobes, 2003). As the current moves through the ground it may encounter resistive layers which cause the current to move faster. If good conductors are present (such as clay layers or the water table), the collection of valid depth sounding data may be impeded as the later parts of decay curves will be dominated by the effects of eddy currents induced in the good conductors (Milsom, 2003). TEM surveys with 100 m transmitter loops have been used to obtain estimates of resistivity down to depths of several hundred metres (Milsom, 2003) (Figure 3.4). Topography can also affect the data collected during TEM surveys. Topographic highs and lows can hinder the interpretation of the data; therefore the ‘background’ electrical conductivity that may be present within the survey area needs to be accounted for. The background conductivity can be used as a base level for a given elevation to compare measurements against. The base level is defined by the conductivity as a function of elevation (Nobes, 2003).

When interpreting the TEM data, short delay times indicate eddy currents in large amounts are present, meaning that relatively poor conductors are present. The eddy currents attenuate rapidly and the later parts of the decay curve indicate currents are circulating in good conductors (Milsom, 2003). TEM surveys can be used to determine depths within the subsurface, especially when horizontally layered ground is present.

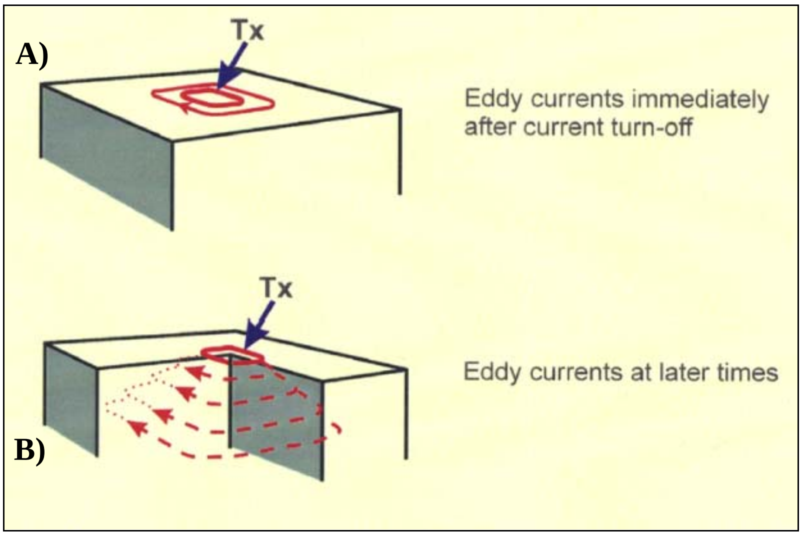


Figure 3.3: TEM eddy currents, (A) initially as current is turned off, and (B) as the eddy currents expand with time (modified from McNeil, 1990 and Loris, 2000).

3.3.2 TEM Methodology

In July 2007, a time-domain electromagnetic (TEM) survey was conducted across the width of the Tekapo sub-basin (Figure 3.1). The purpose of the survey was to attempt to define the top approximately 200 m of glacial gravels and to see at what depth the water table was situated.

For this survey a transmitter cable loop size of 80 m x 80 m was used for each point, except for point 4 where a 40 m x 40 m loop was used due to the proximity of fences (Figure 3.4). Problems arose on the eastern side of the line where electric fences were present that could not be turned off and this has resulted in a large error in data at point 12B. Generally, a distance of at least 200 m from any fence was achieved for each point therefore reducing any interference with the current being induced in the ground. The spacing between each survey point was approximately 1000 m along a line running west to east across the Tekapo sub-basin. The elevation and location of each point was determined using a differential GPS (Figure 3.5)

The data recorded by the PROTEM receiver in the field were downloaded and modelled using the TEMIX software. As the data is modelled the voltages recorded by the receiver are converted to normalised values called apparent resistivity. The TEM response is calculated and compared to the measured response. Initially, data is fitted to smooth models which are then adjusted by varying thicknesses and resistivities of layers until the modelled response matches the measured response. A layered model can then be constructed from the apparent electrical structure of the subsurface (Loris, 2000).

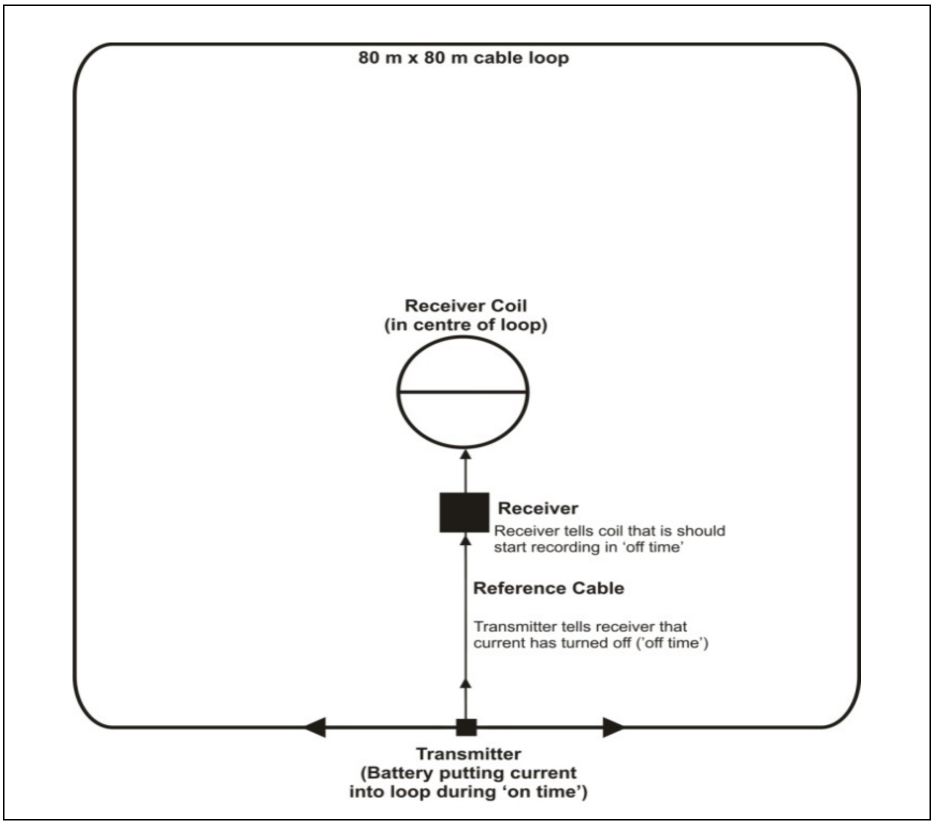
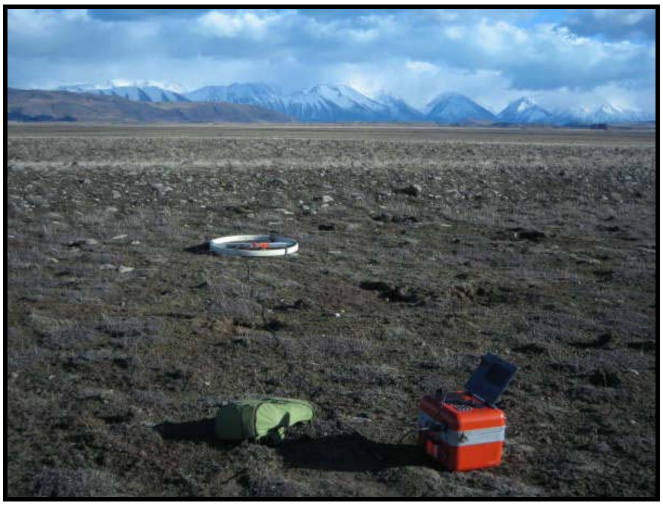


Figure 3.4: TEM transmitter and receiver configuration.

A

C



B

Figure 3.5: A & B) Protem equipment used during the TEM survey. C) Differential GPS system used to record location and elevation of TEM points. The GPS base station was located on a trig point with a known elevation.

Anomalous points that fall outside the trend of other points are likely to be from natural or cultural noise and are not representative of the natural response of the subsurface. An example of the effect of cultural noise, in this case from an electric fence, is shown in the model created for point 12B. The percentage error for this point was 18%, which is very high.

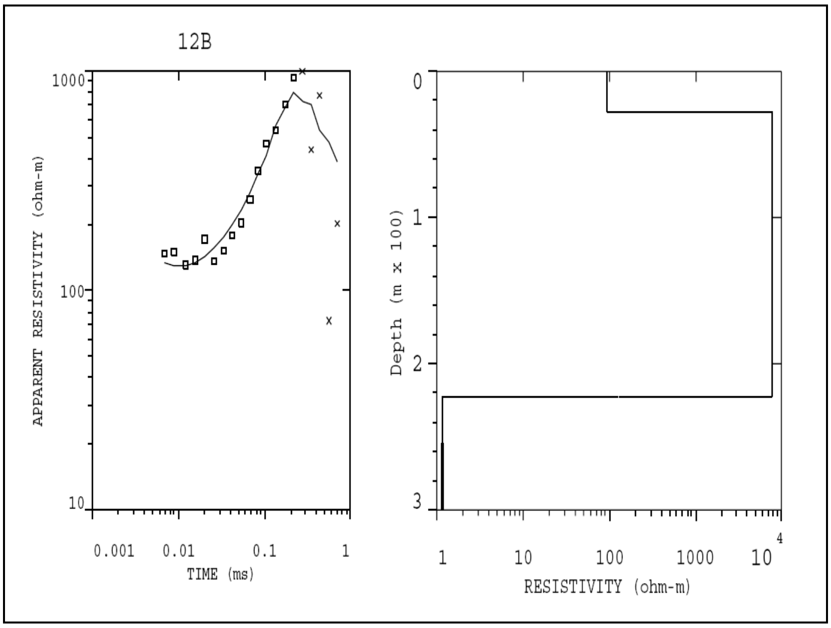


Figure 3.6: The best fit model for point 12B illustrates the affects of an electric fence that surrounded the survey point which could not be switched off.

A 'best fit' model is created by manually adjusting layers and resistivity values and from computer iterations. The model is varied until a minimum deviation between the model and the measured response is obtained. The smaller the spread of data surrounding a best fit line indicates a well constrained model.

3.3.3 TEM Results

Following modelling in TEMIX, equivalence models have been created for each survey point, and the models are contained in Appendix 3E. The depth of penetration achieved for the survey was up to 300 m. This has provided a substantial amount of information at depth. Normally, equivalence models are related to nearby well logs to ground truth the information. However, there is only one well with a bore log (I38/0012) close to the survey line, but it does not provide sufficient detail to constrain the data. The log does not indicate a change in lithologies with depth or the presence of any water bearing units. The majority of the data have been of good quality, where the error rate was below 5%. Some points are slightly above this value, however, and point 12B is much higher. The result of this error, due to cultural noise, is shown in Figure 3.6. The data from point 12B has not been included in the geo-electric model due to the high error value.

3.3.4 TEM Interpretation

The resistivity values have been plotted with regard to depth along the survey line and the resulting model is shown in Figure 3.7. The model indicates that there are three layers with differing apparent resistivity values. The elevation of each change in resistivity is denoted by a point and a resistivity value. The dashed line between the points is an inferred geo-electric boundary as the resistivity values only represent the resistivity of the lithology at a discrete point in the subsurface. The higher resistivities are located in the layer close to the surface, but there are areas of lower values to the west of the Tekapo River and near the alluvial fans on the Mary Range and the Rollesby Range. Higher resistivity values represent material that is less conductive such as bedrock or dry sand lithologies, whereas clays and water bearing units will be much less resistive. However, the entire lithology that may be present at depth must be considered when interpreting the results. For instance, if there is a large presence of clays (such as those found in glacial deposits) the contrast between water bearing units and clay units will mean that high resistivity values may actually indicate the presence of water. Therefore distinguishing what the values actually represent without ground-truthing the data is very difficult.

Two interpretations from the model are suggested: the thinner layer close to the surface represents a unit lacking in water and a high clay content; and the underlying layers represent water bearing units or clay layers. This would indicate that the second layer, of much lower resistivity values, has a high water content, and is likely to be the Mt John Outwash Gravels. The underlying layer with even lower resistivity values, due to a higher clay content, is possibly the Balmoral Outwash Gravels.

The other alternative is that the near surface layer contains water and has higher resistivity values in comparison to the underlying layers due to the fact that the deeper units are more compact and have a higher clay content than the overlying layer. The surface geology of the area to the east of the Tekapo River has been mapped as Post Glacial Alluvial Gravels, and the wells present within that area contain at least 15 m of groundwater at approximately 15 m below the surface. The young alluvial gravels are less compact and have a lower silt/clay content compared to underlying glacial formations. If this scenario is carried further it would indicate that below the second change in resistivity values (blue line) it is possible that the much older Glentanner Formation is present and this would fit with the gravity model shown in Figure 3.2. The increase in elevation of the change in resistivity values to the west of the

Tekapo River also corresponds with the bedrock high indicated in the gravity model. The model also suggests that there are two buried sub-basins.

There could be a number of interpretations of the data, as it is likely there are more than three layers present at depth. Flathe (1976) notes that without a real geological definition of what is present at depth an interpretation of geo-electric measurements is impossible if the number of layers exceeds three. Drilling of bore holes or using other geophysical techniques such as seismic reflection surveys is required to constrain the resistivity data collected and provide a more definitive answer. The TEM geophysical method appears to be fairly successful at delineating the lithological boundaries in the top 250 m. Additional transects may enable characterisation of the geometry of the Pliocene and Pleistocene gravels even further.

3.4 SEISMIC SURVEY

3.4.1 Seismic Reflection and Refraction Theory

Seismic surveys use the propagation of waves of energy to define the subsurface. They are also useful for providing information on water content variations and associated physical property contrasts, as well as the water table (Kearey & Brooks, 1991; Nobes, 2003). Seismic waves are propagated through the subsurface and the travel times of measured waves that are either reflected or refracted at geological boundaries, can be converted into depth values. These values can indicate subsurface interfaces of geological formations. There are two types of waves that pass through the subsurface: P-waves (primary compressional waves) and S-waves (secondary shear waves). P-waves travel faster than S-waves through the same medium. The rate at which the wave travels through the subsurface is determined by the physical properties of the material such as density. The velocities of selected materials are contained in Table 3.2.

Table 3.2: Compressional wave velocities in Earth materials (adapted from Kearey & Brooks, 1991).

Material	P-wave Velocity (m/s)
Unconsolidated Materials	
Sand (dry)	200 – 1000
Sand (water saturated)	1500 – 2000
Clay	1000 – 2500
Glacial till (water saturated)	1500 – 2500
Sedimentary Rocks	
Tertiary sandstone	2000 – 2500
Carboniferous sandstone	4000 – 4500
Cambrian quartzite	5500 – 6000
Other	
Air	300
Water	1400 – 1500
Ice	3400
Granite	5500 – 6000

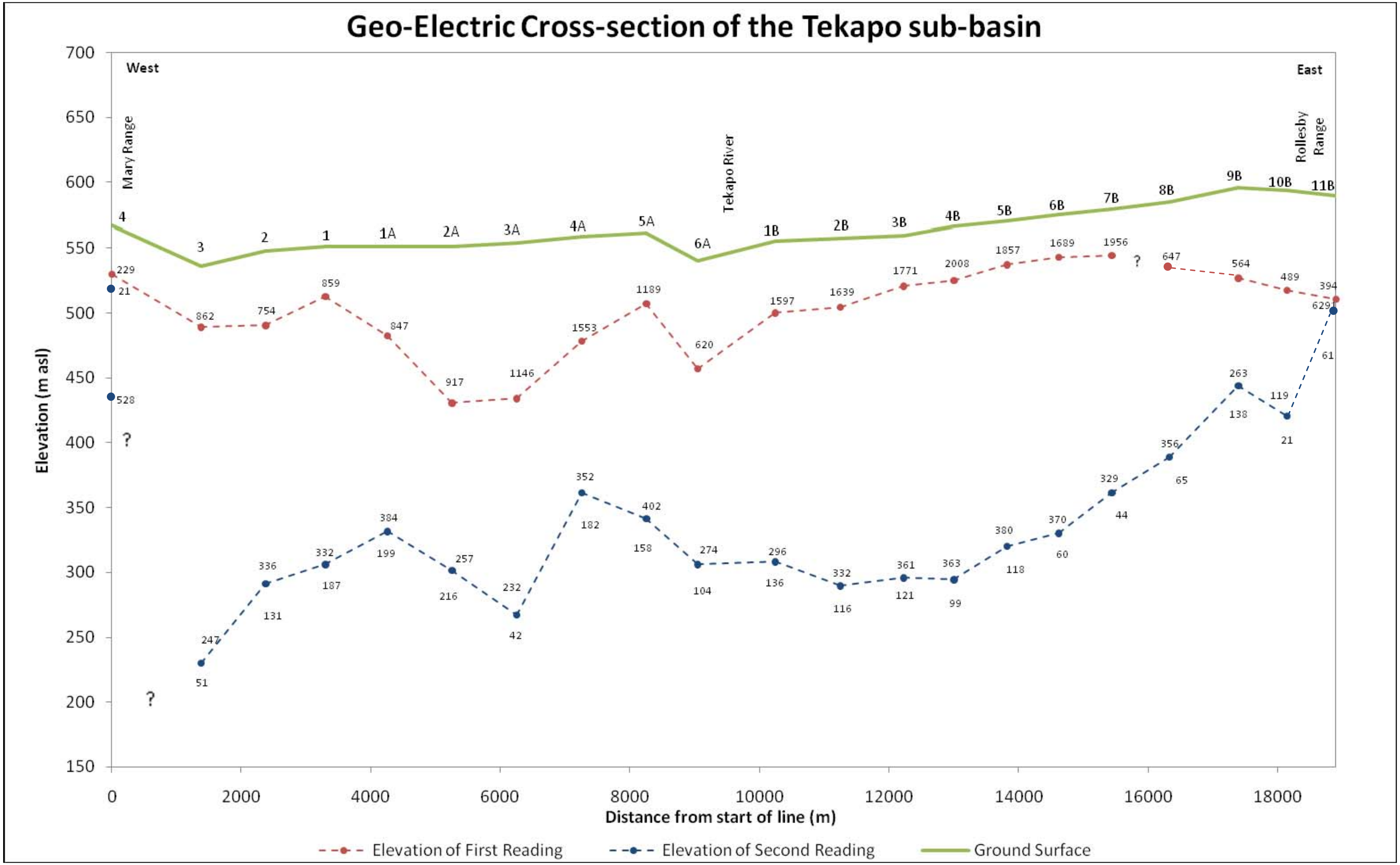


Figure 3.7: Geo-electric cross-section of the Tekapo sub-basin. The dashed red line indicates the elevation at which the resistivity values first changed, the dashed blue line is the elevation of the second resistivity change. Lower values indicate that a less resistive (more conductive) unit is present at that particular location. Apparent resistivity values are shown for each point.

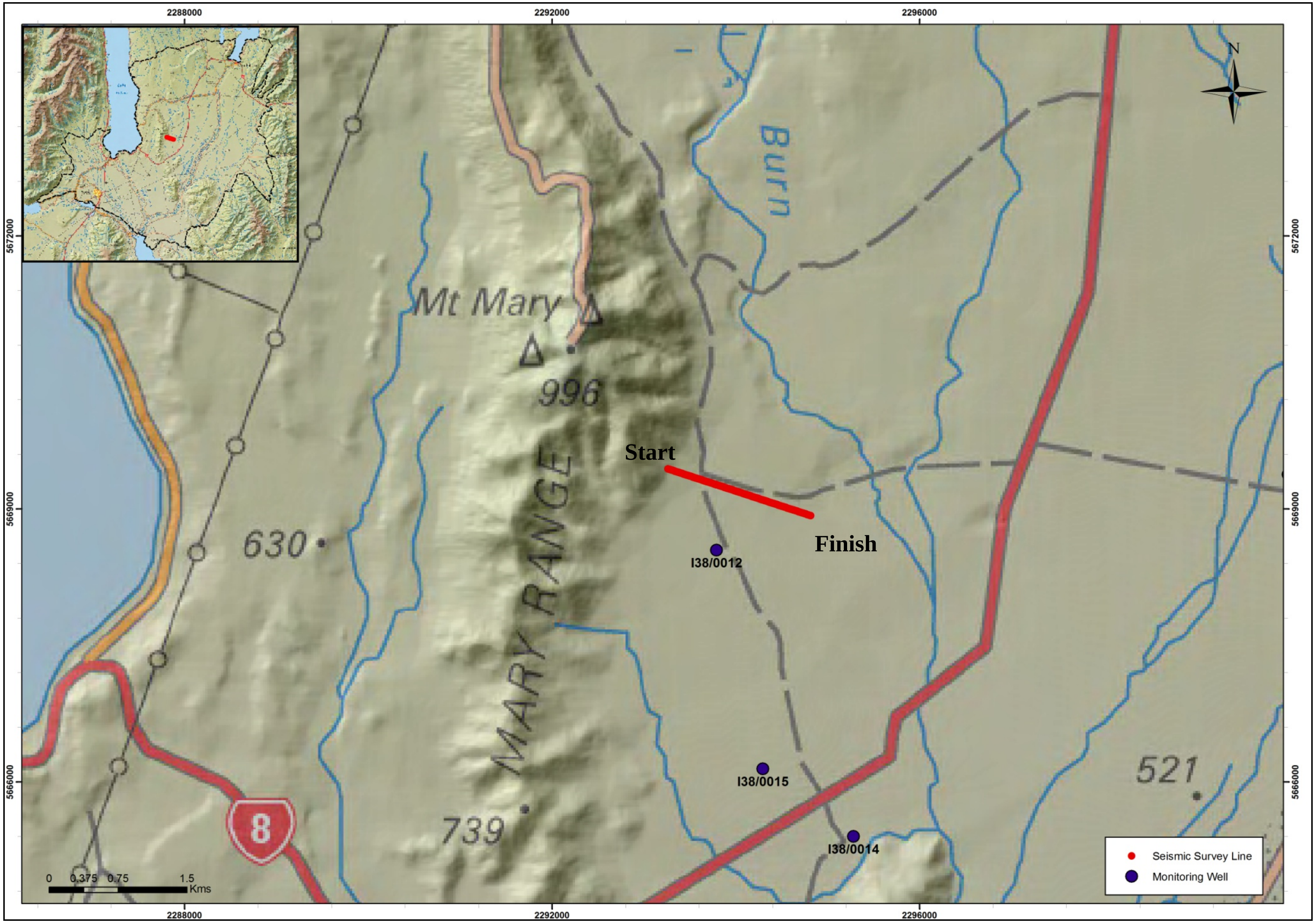


Figure 3.8: Seismic survey line location map (Inset: location of survey line within the field area).

At the point where a seismic wave encounters an interface between two different rock types, a change of propagation velocity will occur due to the differing densities of the two layers. At the interface, the energy of the seismic wave will be split into transmitted and reflected pulses. Figure 3.9 illustrates the change that occurs at the interface between two layers. Across the interface there is an acoustic impedance which determines the proportion of transmitted and reflected energy. The acoustic impedance is determined by the density and compressional wave velocity of a material. In general, the harder the rock the higher the acoustic impedance will be (Kearey & Brooks, 1991).

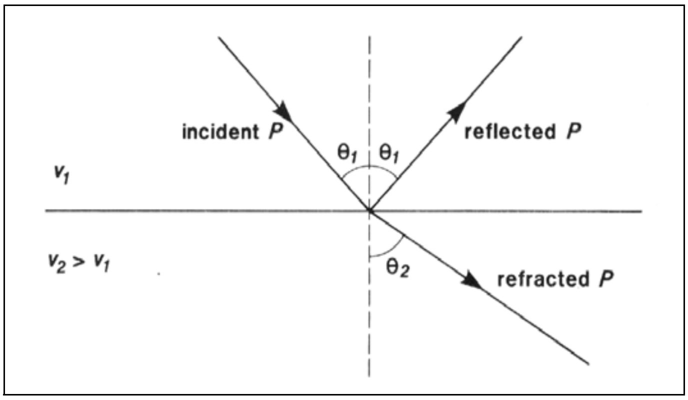


Figure 3.9: Reflected and refracted P-waves incident on an acoustic impedance interface (Kearey & Brooks, 1991).

There are three types of rays that travel through the subsurface from the source to the detector: direct rays – travel in a straight line along the top layer; reflected rays – are obliquely incident on the interface and are reflected back to the surface; refracted rays – travel obliquely to the interface then along the interface before going back to the surface. By analysing the travel time of reflected or refracted rays it is possible to define the depth to the underlying layers (Figure 3.10) (Kearey & Brooks, 1991).

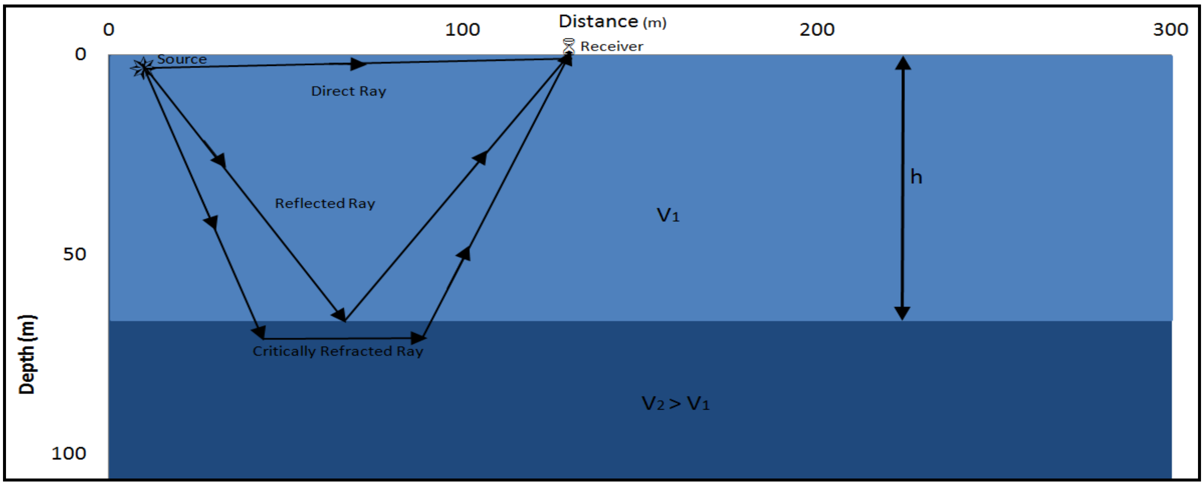


Figure 3.10: In a two layer model waves can be reflected and refracted back to the surface. Where the velocity of layer two (V_2) is greater than layer one (V_1) refracted waves cross the interface and travels through layer two (V_2) along the interface before returning to the surface receiver.

Direct rays and refracted rays are always the first arrivals of seismic energy at a surface detector. The refracted ray overtakes the direct ray at the cross over distance (Xc). Beyond this offset distance the first arrival is always a refracted ray. Refracted rays travel down to the interface at a critical angle, and at the critical distance refracted rays do not return to the surface. At the critical distance, travel times for reflected and refracted rays coincide as they effectively follow the same path. Reflected rays are never first arrivals. In reflection surveying, reflected rays are sought that are not first arrivals and have a very low amplitude as geological reflectors tend to have small reflection coefficients (Kearey & Brooks, 1991). Reflected rays are often hidden by higher amplitude events such as direct or refracted waves. Reflection surveying methods are required to recognise the reflected energy amongst the noise. Recordings normally have small offset distances; however, multichannel recordings are usually taken over a significant range of offset distances (Kearey & Brooks, 1991).

3.4.2 Seismic Methodology

In March 2008 a small seismic survey was conducted on the west side of the Tekapo sub-basin (Figure 3.8). The purpose of the survey was to collect information on stratigraphic detail within the basin-fill sediments down to a depth of approximately 150 m.

3.4.2.1 Sources

To gather enough detail of the subsurface, a source must be powerful enough to penetrate to a sufficient depth and return a reflection wavelet with enough energy to be detected above background and environmental noise. In addition, bandwidth frequency must be high enough to image the subsurface in detail (Finnemore, 2004). The surveys can have either explosive or non explosive sources. Explosive sources have the benefit of creating a signal that contains a broad band of frequencies and therefore a narrow shape which puts a lot of energy into the ground to achieve a greater depth of penetration. There are some disadvantages to this source including: the signal shape is not identical for each shot and the source point cannot be used more than once (Nobes, 2003).

During this project, 70 grams of Powergel™ ammonium nitrate explosive was used for each shot with instantaneous detonators. A total of 85 shots were used with a spacing of 10 m for the first 100 m of the line and then 20 m for the rest of the line. Shot holes were drilled using a rock hammer, with a hole depth of approximately 0.8 m. After placing the explosives, the holes were stemmed with gravel.

3.4.2.2 Receiver (Geophones)

The receivers of the seismic waves are known as geophones, which are electro-mechanical transducers that convert the seismic pulse into an electrical output (Kearey & Brooks, 1991). Geophone sensitivity is dependent on several factors: inherent sensitivity; electrical damping of the frequency response; geophone orientation – most sensitive when vertical; age and usage of geophones – springs within the geophone deform and crack over time; and geophone and subsurface coupling (Finnemore, 2004). For this survey single geophones with a 30 Hz frequency were used with 10 m spacing.

3.4.2.3 Noise

The quality of the seismic data collected can be reduced by natural and cultural noise, the sources of which are shown in Table 3.3. Conditions during the survey for this study were favourable for seismic data collection. However, increasing wind speeds in the afternoon led to vegetation movement which did affect some shot gathers slightly, creating noise in the data.

Table 3.3: Examples of noise that can reduce the quality of data collected in a survey (Finnemore, 2004).

Cultural Noise	Natural Noise
Traffic – produce strong ground roll which can swamp reflection signal	**Streams/Rivers** – produce low frequency noise
Aircraft – produce low frequency noise which can swamp seismic signal	**Trees** – in windy conditions the swaying of any vegetation produces seismic frequency noise
Electric Fences – create electromagnetic inductance creating a spike in seismic data	**Wind** – at high wind speeds plant growth near geophones will affect seismic data
Utilities – high voltage cables induce high harmonic interference which swamps reflection signal	**Rain** – single rain drops can swamp a geophone for >100 ms after impact
Pumps – produce strong acoustic seismic frequency noise and swamp seismic signals	**Marine Waves/Beach Surf** – beaches tend to have a high ambient background noise level from breaking waves
Farming/Agriculture – large groups of moving animals create seismic noise and swamp reflection signals	

3.4.3 Seismic Survey Design

The survey line was 1500 m long, running from the Mary Range in the west towards the Mary Burn in the east (Figure 3.11). The shot spacing was 10 m for the first 100 m, changing to 20 m for the rest of the line. The geophone spacing was 10 m for the entire line. Three cables, with 24 geophones on each, were laid out along the line. After the shots on the first cable were shot, the first cable was rolled to the end of the other next two cables (Figure 3.12). The rolling procedure continued until the end of the line was reached.

The elevation and location of the survey line was measured using a Pro XR Trimble GPS base station and rover with an accuracy of 10 cm horizontal and 20 cm vertical (Figure 3.15).

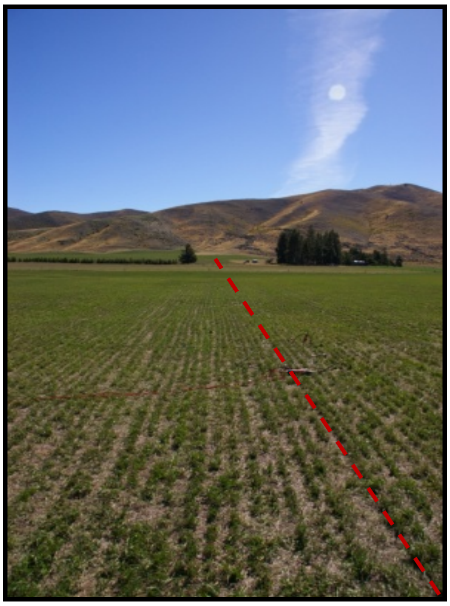


Figure 3.11: Seismic survey line – Mary Range in the distance. Survey line indicated by dashed red line.

Figure 3.12: Charges being detonated along survey line (70 gm PowerGel, and 0.8 m deep holes).

Figure 3.13: Geometrics Stratovisor Seismograph.

Figure 3.14: Detonator – radio blaster.

Figure 3.15: Trimble GPS rover unit used to measure location and elevation of survey line.

The shot gathers were recorded on a 48 channel Geometrics Stratovisor seismograph, with a 0.25 millisecond sampling interval, recorded for 2 seconds at each shot location (Figure 3.13). The charges were detonated with a radio blaster (Figure 3.14). The geometry of the survey is shown in Figure 3.16. The geometry moved from an end-on push spread to a split spread and finally an end-on pull spread.

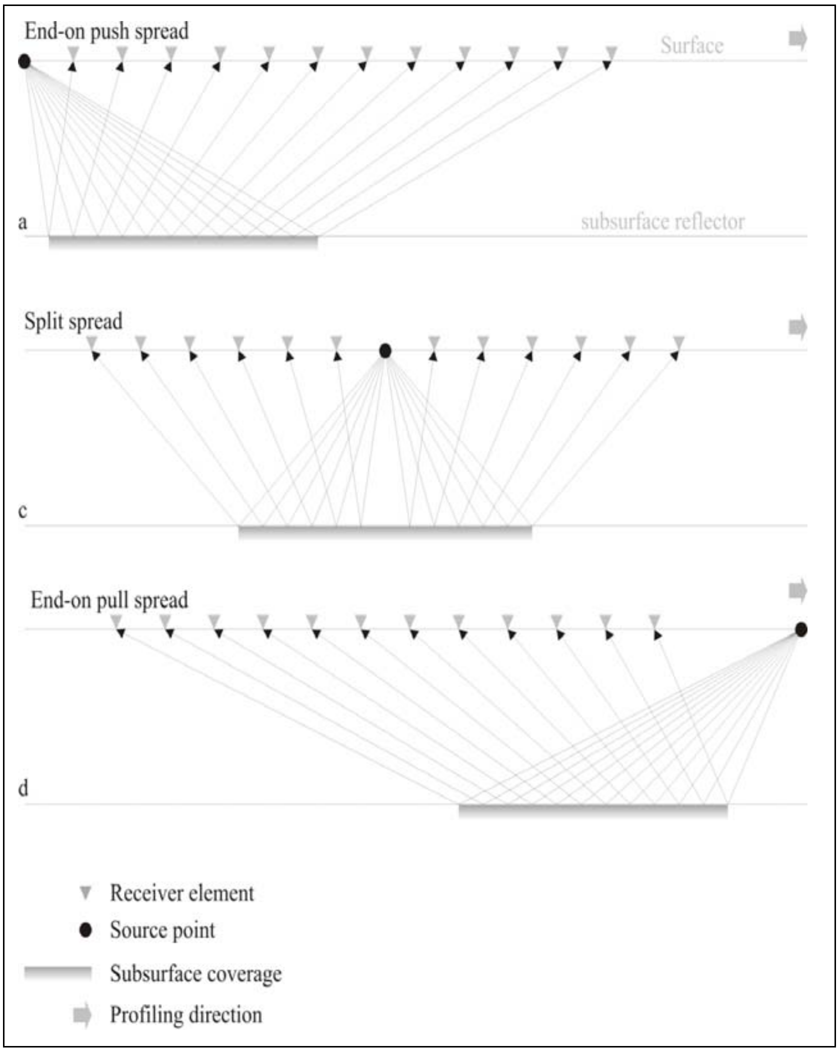


Figure 3.16: Survey geometry (modified from Finnemore, 2004).

3.4.4 Seismic Reflection Processing

Reflection seismic data is acquired as shot gathers. Once acquired, the seismic data needs to be processed to remove or reduce unwanted noise to enable the refraction data to be highlighted. The purpose of processing is to extract information regarding lateral and vertical geometry of the refraction boundaries from the shot gathers to create a subsurface image with the boundaries in their correct geometric position and depth (Finnemore, 2004). The end result of processing is to modify the data and to display it as a stacked seismic profile which can be used for interpretation purposes (Anderson, 2000). The key seismic processing stages and assumptions and principles are contained in Appendix 3F. To be able to process the seismic reflection data correctly the acquired data must have a high sampling rate, a long enough record length, and accurate trigger timing. The three-dimensional geometry of each receiver and source of each shot is required to convert shot gathers into the Common Mid Point (CMP) domain, and is usually obtained by using differential GPS (Finnemore, 2004).

3.4.5 Seismic Refraction Results

The data collected from the seismic refraction survey were proceessed using the Visual Sunt program and then reviewed. Nineteen shot gathers were selected for use along the seismic line and a simple two layer refraction model calculated at those locations (see Appendix 3G). Traces which recorded noise from either wind or other external factors were removed from the shot gathers to make interpretation clearer. The first breaks of each shot gather were picked by eye. On each shot gather the velocity of each layer identified was measured using the Visual Sunt program. The cross over distance (Xc) is the distance at which the direct and refracted arrivals have the same travel time (Kearey & Brooks, 1991). Using the cross over distance the depth to the layer with the faster refractor beneath the cross over point can be determined, in this case V_2 (Figure 3.17). This simple calculation is based on the assumption taht the refractor layer is not dipping and is continuous across the shot gather. The velocities and the cross over distance are then put into the equation below to determine the thickness of layer 1 for each selected profile, before being plotted in Excel to create the refraction model. The calculations for each profile are contained in Appendix 3H. Figure 3.18 is an example of the velocity lines picked for profile 102. Assuming a two layer model, the thickness below the surface of layer 1, with an average P-wave velocity varying from 1053 m/s to 1839 m/s, varies from 8 m to 26 m. The average P-wave velocity of layer 2 varies from 2504 m/s to 2997 m/s.

$$= [x_{\downarrow}c/2((V_{\downarrow}2 + V_{\downarrow}1)/(V_{\downarrow}2 - V_{\downarrow}1))] \uparrow(1/2)$$

h = thickness of layer

χ_c = cross over distance

V_1 = velocity of layer 1

V_2 = velocity of layer 2

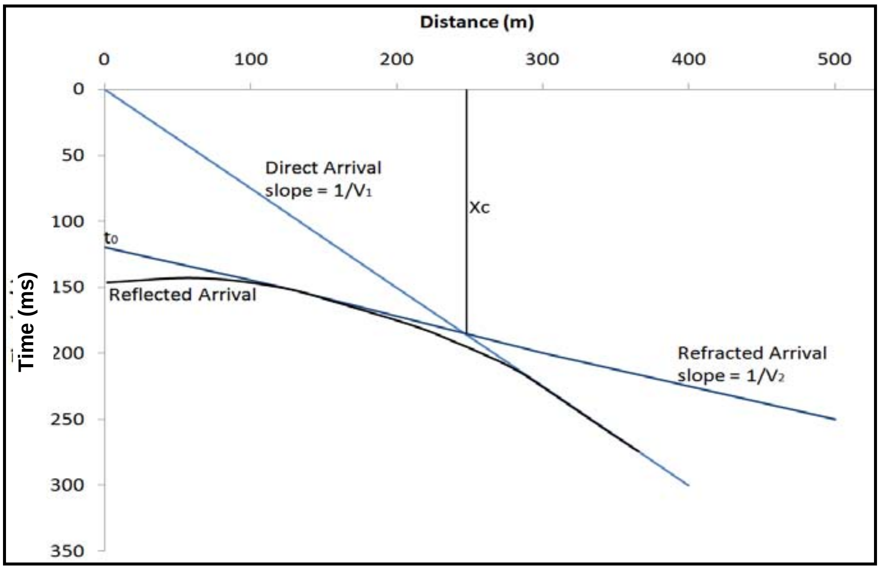


Figure 3.17: Direct, refracted, and reflected arrivals. The slope of the direct and refracted arrivals, in conjunction with the cross over point are used to calculate the velocity of each layer for the seismic refraction model.

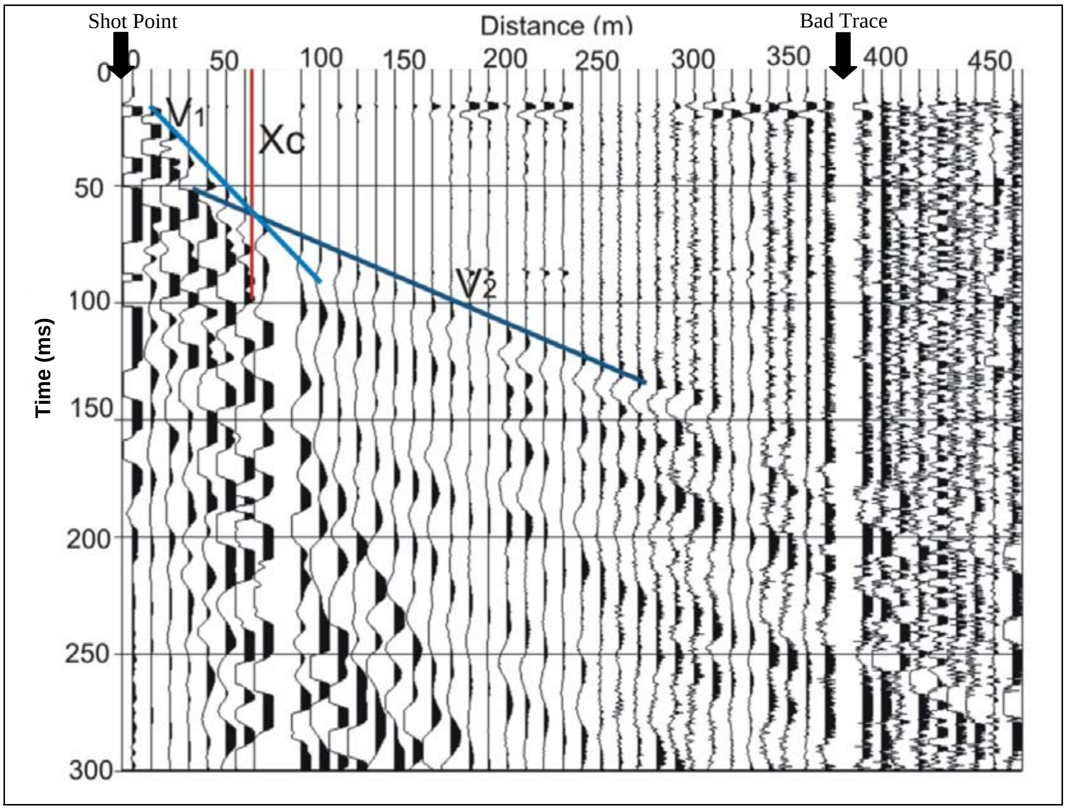


Figure 3.18: Profile 102 indicates the ray tracing used to determine the velocities for each layer.

3.4.5 Seismic Refraction Interpretation

Following the processing of the data a model was created (Figure 3.19). To the west, from the start of the line, the average P-wave velocity of layer 1 is approximately 1030 m/s. This low velocity is indicative of a mixed, unconsolidated formation. This area has previously been mapped as an alluvial fan. At approximately 620 m along the survey line, the average velocity of layer 1 becomes 1839 m/s. The velocity suggests an unsaturated unit, containing very permeable gravels. Layer 2 has an average velocity ranging from approximately 2500 m/s to 3000 m/s. The higher velocity of this layer suggests a lithology change to a higher silt/clay content. Based on the changing velocities along the survey line, layer 1 is an alluvial fan in the west and a buried outwash channel in the east. It is possible that this buried channel is an abandoned channel of the present day Mary Burn which is currently located 2100 m to the east of this area. The area covered by the seismic survey line has been mapped as the Balmoral Formation. It is suggested that layer 2 is the Balmoral Formation and that the overlying unit is reworked Balmoral Formation from the glacial recession period. It should also be noted that as only a two layer model was used for layer identification, it is possible that a third layer was present (denoted by dashed line in Figure 3.19) and that it continues under the alluvial fan to the west of the buried channel.

3.4.6 Seismic Reflection Interpretation

Following processing of the seismic reflection data, a profile was produced for interpretation (Figure 3.20). The seismic reflection data are contained in Appendix 3I. A strong, continuous reflector can be seen at a depth of approximately 175 m to 200 m. It is suggested that this strong reflector represents the top of the Glentanner Formation. The reflector is long and continuous (>1000 m long), and onlaps onto the Mary Range in the west. It is unlikely that this reflector represents any of the glacial formations as it is such a flat, long layer which has not been reworked like the glacial formations.

Overlying this reflector is approximately 200 m of glacial gravels which have an internal velocity of approximately 2900 m/s. This velocity for alluvial gravels is very high when comparing velocities to gravels within the Canterbury Plains area. The high velocity is possibly from compaction of the gravels from overriding ice advances; a high fines content within the voids of the gravels displacing air (velocity ~330 m/s) or water (velocity ~1800 m/s) from the voids; and/or the presence of schist particles within the alluvial gravels which have a higher velocity due to their mineralogy.

Another reflector can also be seen sharply dipping downwards away from the Mary Range. This represents the top of the Torlesse bedrock, which outcrops in the Mary Range at the start of the seismic survey line. The bedrock reflector is lost at depth, however, there are hints of slightly folded reflectors at depth within the bedrock.

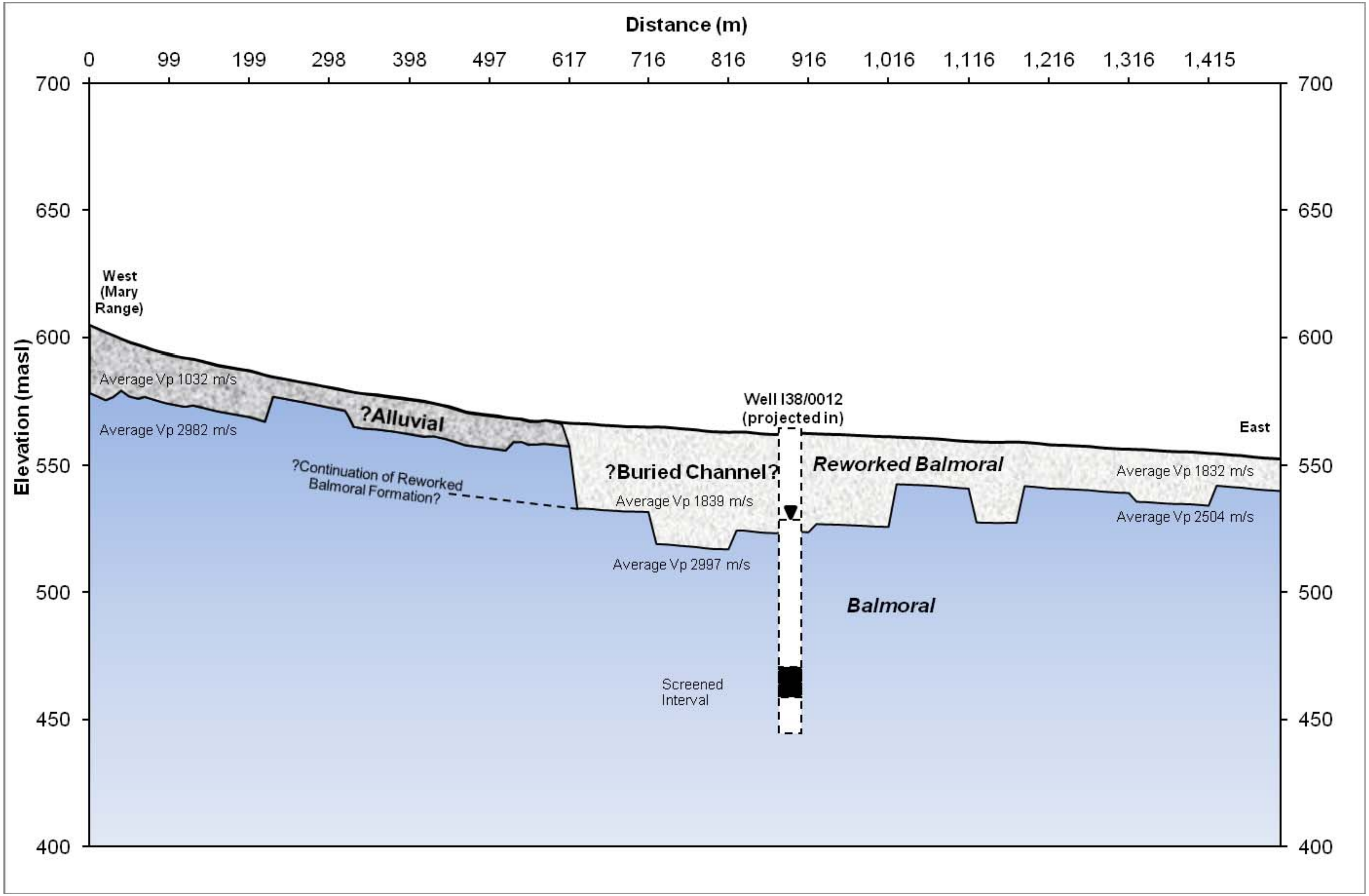


Figure 3.19: Two layer seismic refraction model. Average velocities of each layer are noted to indicate the changing velocities from west to east. The bore log for well I38/0012 has been projected back into the line (its actual location is ~600m to the south of the survey line). It is possible that more layers are present at depth.

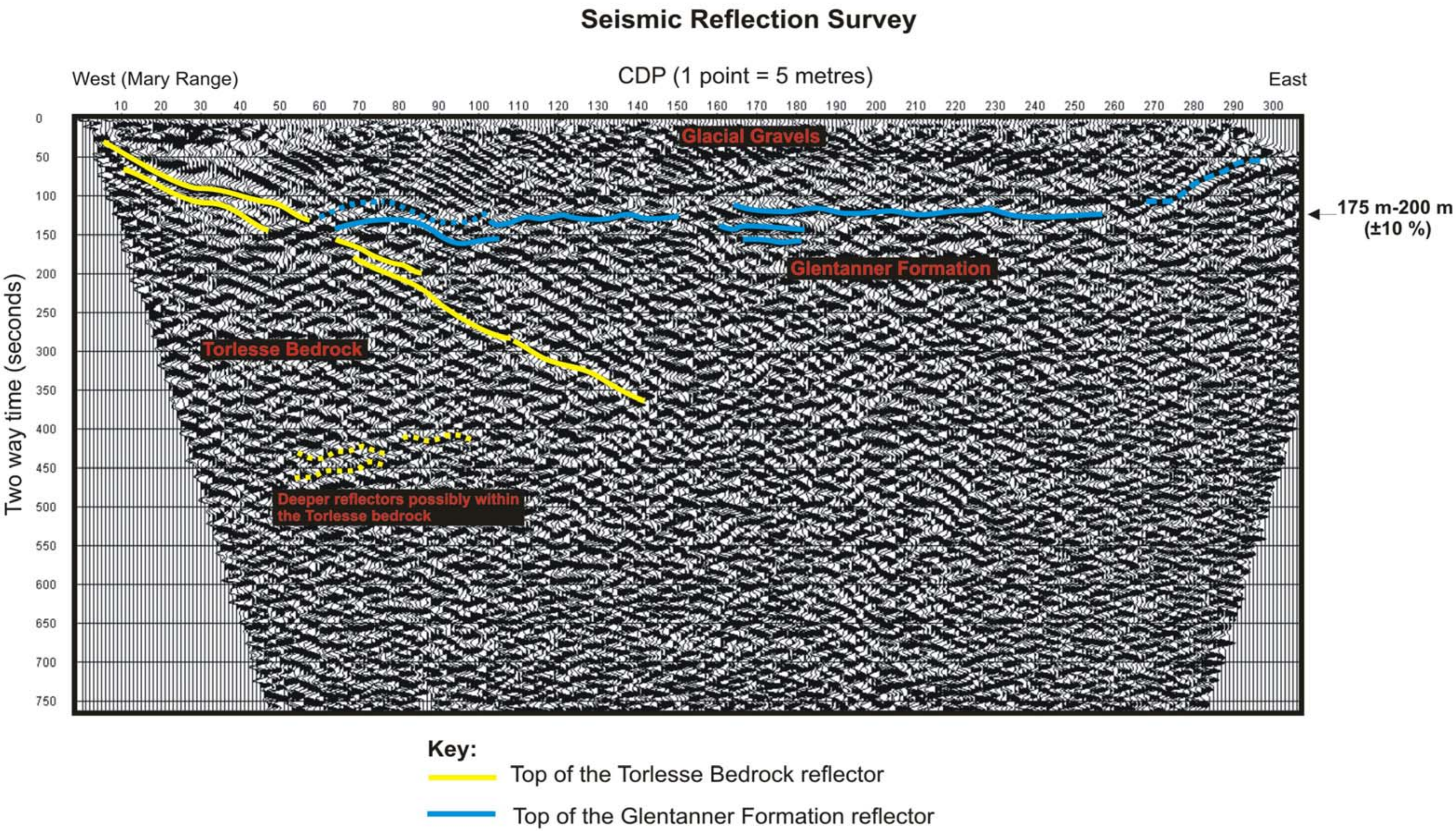


Figure 3.20: Processed seismic line - not migrated.

3.5 CHAPTER SUMMARY

A large number of geophysical surveys have been carried out within the Mackenzie Basin. Initially, the purpose of the surveys was to define the bedrock depth and geological boundaries for canal construction. In addition, investigations to locate possible groundwater that may create problems for canal and dam construction were undertaken. More recently geophysical surveys have concentrated on active fault zones within the basin. Large scale surveys have also been conducted to investigate crustal depth and the activity of the nearby Alpine Fault.

Geophysical surveys were carried out during the course of this study to further define the structure of the basement in terms of depth to bedrock and stratigraphic detail of the overlying gravels. It was also hoped that the surveys would provide more detail on the occurrence of groundwater. The three surveys conducted were gravity, TEM, and seismic.

The gravity survey was conducted from west to east within the Tekapo sub-basin. The purpose of the survey was to define the depth to bedrock within this area. Twenty observation stations were measured along a 22 km line, which were looped back into two base stations to correct for drift. The data collected have been corrected for latitude, Bouguer, and free-air effects. The data have been modelled using the GM-Sys software. However, gravity modelling is a non-unique process and a number of models fit the same data. The model that was chosen for this study based on known geological units and rock densities, indicates that the bedrock has topography and possibly divides the Tekapo sub-basin into a further two sub-basins at depth. The model also suggests that the overlying gravels are thick at this location, but it is difficult to quantify the thickness of each layer. The gravels appear to be nearly 1000 m thick in places.

A TEM survey was run along the same survey line as the gravity survey within the Tekapo sub-basin. Good quality data was recorded in the majority of sites with a depth of penetration up to 300 m. One site did record bad data due to an electric fence that surrounded the TEM survey site. The data from this site has not been included in the model. The data recorded have been converted to apparent resistivity values and modelled to create equivalence models. The resistivity values from the equivalence models have been used to create a geo-electric cross section of the sub-basin. The data indicate that there are a number of possible interpretations. It is suggested that either the high resistivity values represent shallow groundwater and that the lower values from underlying layers are due to the presence of highly conductive (and therefore lower resistivity) clay units at depth. The alternative is that the shallow gravels close to the surface are highly resistive (low conductivity) and that the underlying layer is due to the presence of groundwater. Further investigations are required to ground-truth the geophysical data. However, the TEM method appears to be useful for delineating geological boundaries and possible groundwater occurrences at depth.

In early 2008 a small seismic survey was carried out along a 1.5 km survey on the east side of the Mary Range within the Tekapo sub-basin. The data collected have been used to create a seismic refraction model. The refraction model illustrates the high seismic velocity contrasts between the layers. The model has only used a two layer model, but more layers could be present at depth. The model identifies the known alluvial fan which overlies the Balmoral Outwash Gravels. Buried channels of possibly reworked Balmoral Outwash Gravels can also be seen. The results from the seismic survey indicate that the method will be very useful for the delineation of buried channels that may contain groundwater.

The seismic survey data have also been used to create a seismic section. A strong reflector at a depth of approximately 175 m to 200 m is thought to represent the top of the Glentanner Formation. The overlying 200 m of glacial gravels has a very high velocity (~2900 m/s) and this is thought to be due to either compaction of the gravels or lithological composition. A reflector from the Torlesse bedrock can also be seen sharply dipping downwards below the gravels.

The depth of the reflector (top of the Glentanner Formation) is at approximately the same depth as the deeper layer defined within the geo-electric cross-section from the TEM survey. This suggests that the resistivity data is imaging the Glentanner Formation across the Tekapo sub-basin and indicates that the overlying glacial gravels have a thickness ranging from 200 m to 300 m, and that the Glentanner Formation is very thick in places (>700 m thick). The lower resistivity values seen within the Glentanner Formation are likely to be due to lithological composition (high clay content) and being saturated with water. Even though the Glentanner Formation is likely to be saturated with water it still represents the hydrogeological boundary as the formation is too claybound to yield any water. The same situation is seen in North Canterbury where the comparative Kowai Formation does not produce groundwater due to its claybound nature, but is fully saturated with water (M. Finnemore pers. comm., 2008).

As the seismic and TEM data correspond well, the TEM geophysical technique, which is easier and cheaper to run compared to a seismic survey, can be reliably used to further define the lithological boundaries throughout the Mackenzie Basin.

CHAPTER 4

HYDROGEOCHEMISTRY

4.1 INTRODUCTION

Defining the chemical composition of groundwater and surface water can help to define aquifer characteristics and recharge sources of groundwater systems. Collecting samples from different locations and periods of time can indicate spatial and temporal trends of groundwater flows. During this study samples were collected from wells distributed throughout the Mackenzie Basin and the analyses of the samples have been compared to results from water samples collected from the basin during 2005 by Environment Canterbury.

During February and March 2005, 14 wells within the study area were sampled for groundwater quality purposes. All samples were analysed for pH, conductivity, nitrate nitrogen, ammonia nitrogen, alkalinity, chloride, sulphate, silica, calcium, magnesium, sodium, potassium, iron, and manganese (Smith & Hanson, 2006).

4.2 SAMPLING PROGRAMME

In October 2007 water samples from 15 wells and three lakes were collected by Environment Canterbury staff and the author. In December 2007 another two wells (H38/0188 and I38/0053) were sampled along with a well (H38/0057) which was sampled by the landowner. The locations of the wells sampled are shown in Figure 4.1. The sites were selected based on spatial distribution, well depth, and accessibility. Within the Tekapo sub-basin eight well samples and one lake sample were collected. Within the Twizel sub-basin ten well samples and two lake samples were collected. The types of analyses for all of the samples are listed in Table 4.1. The sample collected by the landowner was analysed for the same chemical parameters as the samples collected by Environment Canterbury with the exception of aluminium, ammonia nitrogen, and reactive phosphorus. All analyses were undertaken at the laboratory at Environment Canterbury and the results of the analyses for each water sample are contained in Appendix 4A. Field measurements were also collected with portable meters that measure pH, water temperature, conductivity, and dissolved oxygen (Figure 4.2).

Figure 4.1: Location of water sampling sites within the Mackenzie Basin. The four red coloured sites are samples collected in 2005.

Table 4.1: Chemicals analysed for in the chemical sampling programme.

Major Cations	**Major Anions**
Potassium (K^+)	Bicarbonate (HCO_3)
Sodium (Na^+)	Chloride (Cl^-)
Calcium (Ca^{2+})	Sulphate (SO_4^-)
Magnesium (Mg^{2+})	Nitrate Nitrogen (NO_3^--N)

Minor Ions	**Non Ionic**
Ammonia Nitrogen (NH_4^+-N)	Reactive Silica (SiO2)
Fluoride (F^-)	
Iron (Fe^{++})	**Heavy Metals**
Manganese (Mn^2)	Arsenic (As)
Aluminium (Al^{+3})	
Boron (B)	
Reactive Phosphorus (P)	

Of the 17 wells sampled, 12 were sampled using installed pumps to purge the water from the casing. Six wells were sampled using a portable Grunfos submersible mini pump with a portable generator (Figure 4.3). This had a pumping rate capability of up to 0.5 L/s. The wells were purged with three times the volume of water contained within the well. The purging time was calculated by multiplying the volume of water within the well by three, and dividing the multiplied volume by the pumping rate. All samples were field filtered with a 0.45 µm membrane and collected in plastic bottles (with preservative where required).

To extend the data for interpretation purposes, samples from four wells collected during February 2005 have been included with the 2007 graphical results. The four samples are from H38/0004, H38/0032, H38/0035, and I38/0054. It should be noted that the results for these four samples may not be directly comparable to the 2007 results as they were collected two years apart and at different times of the year.

Figure 4.2: Example of the portable meters used to collect field data such as pH, conductivity, temperature, and dissolved oxygen levels.

Figure 4.3: Portable Grunfos pump used to collect samples from deep wells that did not have a pump installed.

4.3 GROUNDWATER CHEMISTRY TRENDS

The results of the 2005 and 2007 water sample analyses are listed in Table 4.3 and Table 4.4 respectively (see Appendix 4B). The two sets of results are compared in Table 4.5 (see Appendix 4B). The distribution of major cation and anion concentrations, in milliequivalents per litre (meq/L), for samples collected in October 2007 are illustrated in Figure 4.5 and Figure 4.7 respectively. Figure 4.6 and Figure 4.8 show the cation and anion concentrations for samples collected during February 2005 for comparison (see Appendix 4B). In general, the chemistry of the groundwater indicates that it is enriched in calcium and sodium cations as well as bicarbonate anions. Potassium, sulphate, chloride, and nitrate nitrogen are present in lower levels. There is a greater proportion of magnesium concentration in the Tekapo sub-basin compared to the Twizel sub-basin. The dominant cation is calcium and the dominant anion is bicarbonate. The calcium-bicarbonate dominance is typical of young groundwater within New Zealand (Rosen, 2001), as the groundwater has not developed along the Chebotarev sequence (Figure 4.4).

Although spatially separated, the chemistry for all three lake samples is almost identical. This is likely to be caused by the fact that Lake Tekapo and Lake Pukaki are connected via the canal system for hydropower generation purposes, and this will create a mixing of lake water. In addition, one well (H38/0051) has a similar chemistry to that of the lakes. It is suspected that this well is encountering leakage from Lake Ruataniwha at depth. The water within Lake Ruataniwha is from the Ohau and Pukaki canal system which carries water from Lake Ohau and Lake Pukaki.

Comparison of the 2005 and 2007 results indicate that there is an increase in ion concentration over time, but this could also be due to the different times in the year that the samples were collected (February and October). Two wells show a change in chemistry between the two sets of samples. Well I38/0015 indicates an increase in the proportion of calcium and bicarbonate, and well I37/0009 has had a large increase in the level of potassium along with a lack of magnesium present in the 2007 sample. All analyses of this well, both in the field and in the lab, have had a significant change over time

In aquifers where primary carbonate minerals are not common, the source of bicarbonate is CO_2 within the air and soil along with low concentrations of carbonate minerals present as weathering products (Deutsch, 1997). Major cations and anions present in solution are usually present in moderate concentrations within host rocks, but have a high rate of solubility in comparison to other less soluble minerals (for example silica), making their concentrations higher in solution (Deutsch, 1997).

Rosen (2001) notes that defining the chemical composition of water derived from sands and gravels can be difficult as aquifer materials can be a mixture of many different lithologies. In New Zealand, groundwater systems tend to have high flow rates and low residence times, and therefore the system may not have come into equilibrium within aquifer lithologies. Therefore, determining the predominant control of water chemistry can be difficult (Rosen, 2001). In New Zealand the most common type of groundwater is a Ca-Na-HCO_3 solution, followed by Ca-HCO_3. The dominance of HCO_3 indicates that the groundwater is relatively young and near the surface. New Zealand groundwater rarely evolves past the HCO_3 stage in the Chebotarev Sequence (Rosen, 2001).

Chebotarev (1955) showed that groundwater evolves through a cycle towards the chemistry of seawater. In young, shallow groundwater bicarbonate will be the dominant anion and older, deeper water will be dominated by chloride anions. This sequence has been illustrated by Freeze & Cherry (1979) (Figure 4.4). The sequence can be divided into three zones, where HCO_3 is dominant in conjunction with low total dissolved solids (TDS), which indicates areas where active groundwater is flushing through well-leached rocks (Freeze & Cherry, 1979). The ability of groundwater to move through this sequence is also reliant on mineral availability and solubility along groundwater flow paths (Freeze & Cherry, 1979).

Travel along flow path $\Rightarrow$

$\mathbf{HCO_3 \Rightarrow HCO_3 + SO_4 \Rightarrow SO_4 + HCO_3 \Rightarrow SO_4 + Cl \Rightarrow Cl + SO_4 \Rightarrow Cl}$

Increasing age $\Rightarrow$

Figure 4.4: Chebotarev sequence showing the evolution of groundwater towards the chemical composition of seawater (Freeze & Cherry, 1979)

A comparison of major cations and anions with other areas within the Canterbury Plains as well as the Wanaka Basin are summarised in Table 4.2. The Wanaka Basin has been included for comparison as the area is similar in geography, climate, and geological structure as the Mackenzie Basin. The Mackenzie Basin has a similar chemistry composition to both the Hinds Rangitata Plain area and the Upper Selwyn Catchment area, both of which are alluvial areas dominated by greywacke. The alluvial Wanaka Basin has a high Ca-HCO_3 content due to the weathering of metamorphic Otago schist. The Waipara Alluvial Basin is dominated by a limestone lithology, demonstrated by a very high Ca-HCO_3 concentration. The distribution of chloride levels also demonstrates that chloride concentrations decrease further inland, as the highest concentrations are found in the Waipara Basin close to the east coast.

Table 4.2: Comparison of cations, anions, silica, and O18 from areas in the Mackenzie Basin, Canterbury Plains and the Wanaka Basin.

	AVERAGE				
Location (Year Sampled) (Author)	**Mackenzie Basin (2007) (This Study)**	**Hinds Rangitata Plain (2006) (Domissee)**	**Wanaka Basin (1995) (Rosen & Jones)**	**Upper Selwyn Catchment (2005) (Vincent)**	**Waipara Alluvial Basin (2000) (Loris)**
Number of Samples	21	32	67	27	39
Ca (mg/L)	11.2	13.8	44.7	13.6	44.0
Mg (mg/L)	2.3	4.7	6.4	4.3	6.9
Na + K (mg/L)	9.1	10.0	8.0	9.3	33.1
HCO_3 (mg/L)	62.4	46.5	152.1	52.6	158.6
SO_4 (mg/L)	5.4	11.0	17.2	6.5	17.2
Cl (mg/L)	1.3	6.4	2.0	8.4	41.1
NO_3-N (mg/L)	0.4	5.2	2.4	4.5	3.1
SiO_2 (mg/L)	11.6	15.2	11.7	15.4	19.6
Dominant Ion	Ca-HCO_3	Ca-HCO_3	Ca-HCO_3	Ca-HCO_3	Ca-CO_3/Na-CO_3
Oxygen 18 (‰)	-11.05	-8.9	-	-8.7	-8.2
	RANGE				
Ca (mg/L)	3 - 32	7 - 22	13 - 130	6 - 20	10 - 220
Mg (mg/L)	0.3 - 7.1	1 - 9	1 - 22	2 - 8	2 - 18
Na + K (mg/L)	2 - 68	5 - 23	3 - 33	5 - 16	15 - 110
HCO_3 (mg/L)	13 - 145	22 - 74	47 - 309	38 - 97	24 - 470
SO_4 (mg/L)	0.5 - 31	2 - 37	1 - 97	1.2 - 16	1.6 - 91
Cl (mg/L)	0.3 - 4	1 - 54	0.5 - 32	4.2 - 13	7.1 - 300
NO_3-N (mg/L)	0 - 2	0.5 - 12	0 - 42	0.4 - 15.3	0 - 17
SiO_2 (mg/L)	3.6 - 18	8.2 - 18	8.4 - 15.8	11 - 19	7.4 - 31
Oxygen 18 (‰)	-9.6 to -12.5	-8.2 to -9.8	-	-7.9 to -8.9	-7.2 to -8.7

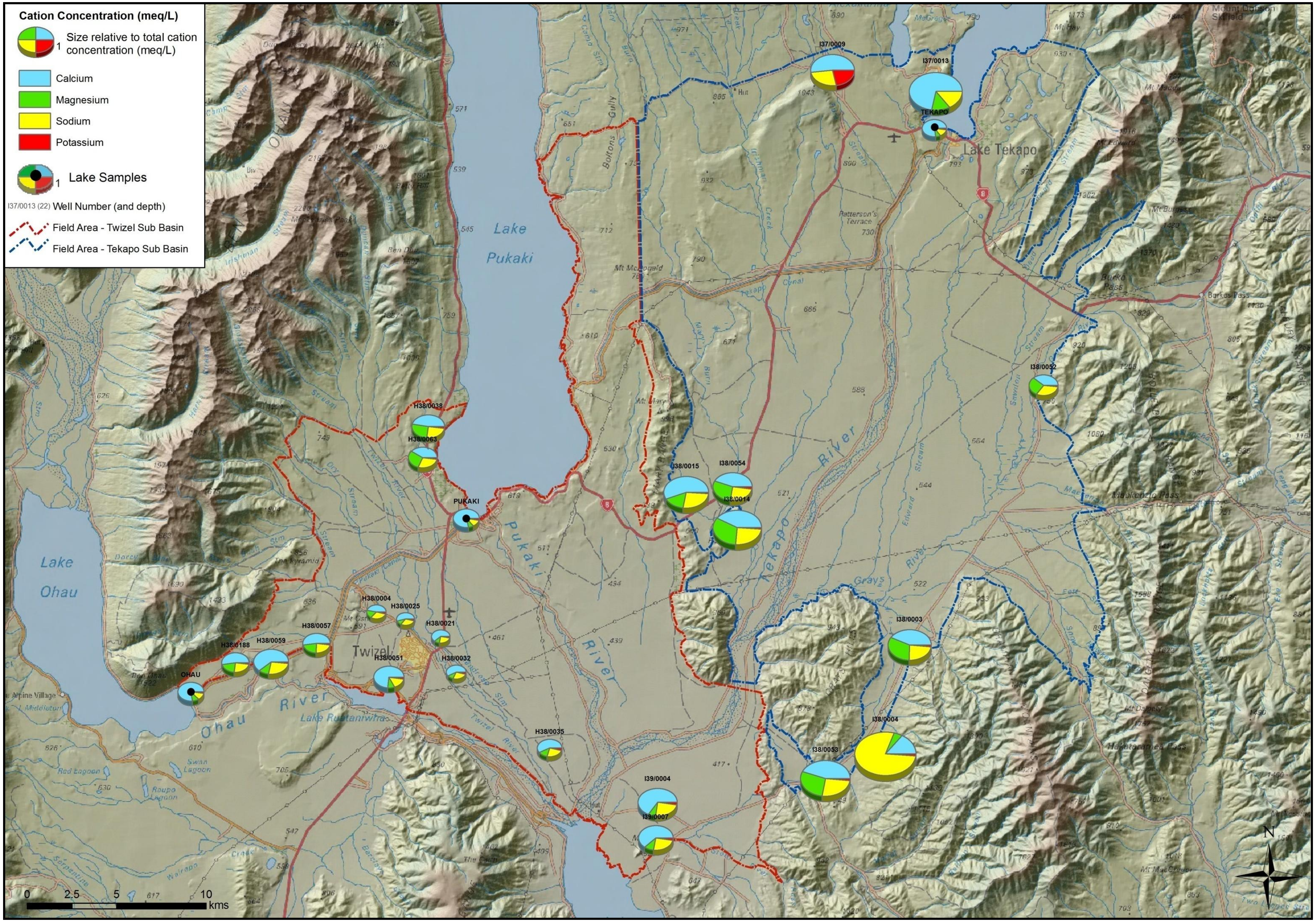


Figure 4.5: Cation concentration throughout the Mackenzie Basin for the October 2007 survey.

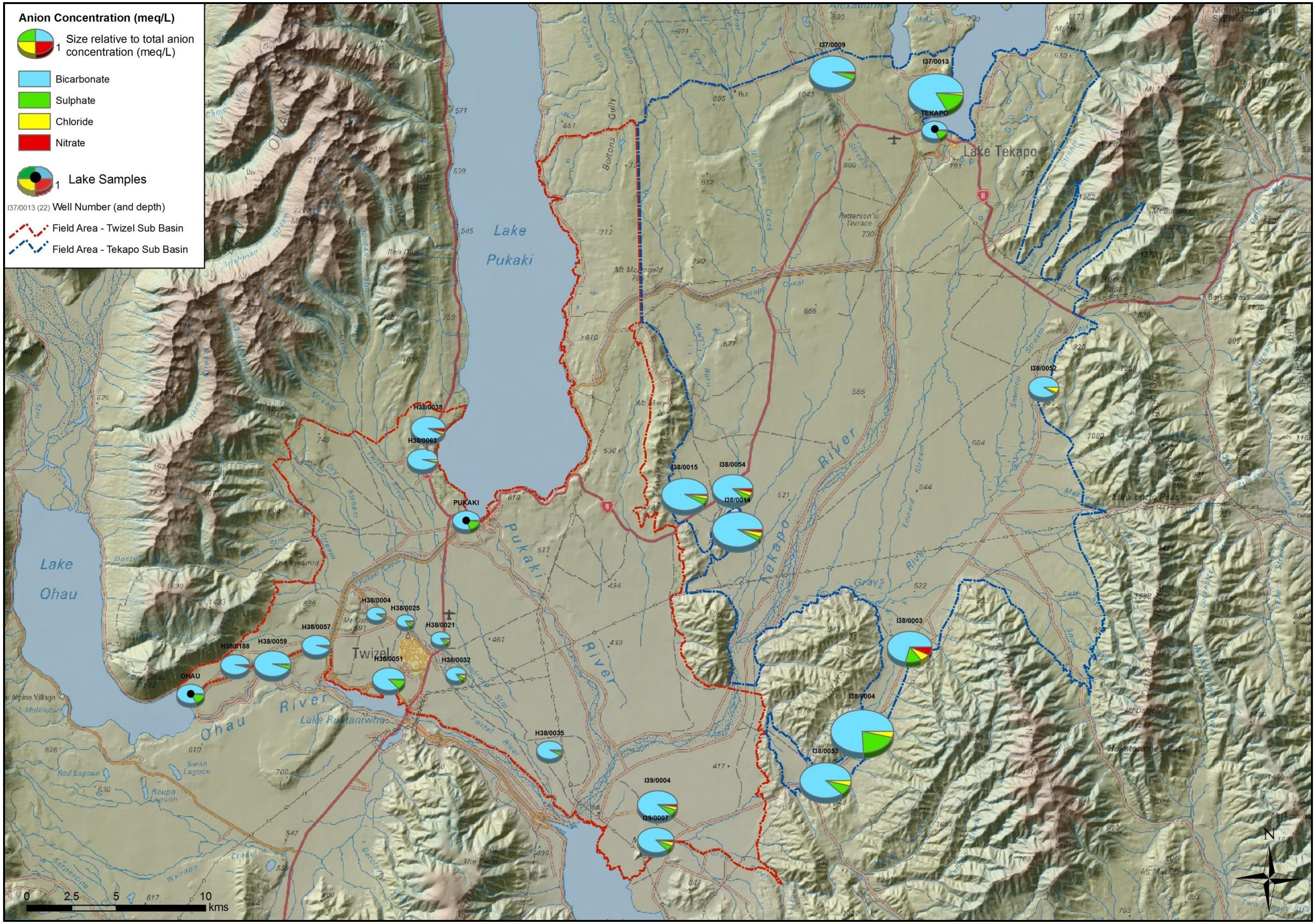


Figure 4.6: Anion concentration throughout the Mackenzie Basin for the October 2007 survey.

4.4 MAJOR CATIONS

4.4.1 Calcium

The sources of naturally occurring calcium are from carbonates (calcite, aragonite, and dolomite), sulphates (anhydrite, gypsum), fluorite, plagioclase feldspars, pyroxene and amphiboles (Hem, 1992; Hounslow, 1995; Rosen, 2001). Hem (1992) notes that calcium occurs in silicate minerals that are produced during metamorphism however, the concentration is generally low as the rate of weathering is slow. Calcium carbonate is commonly present as cement between particles or partial filling of interstices in sandstones (Hem, 1992). The main sink for calcium is ion exchange onto montmorillonite clays (Rosen, 2001). The composition of plagioclase feldspar lies between pure calcium and pure sodium and will produce both along with soluble silica during rock weathering, and under some conditions the solution may attain saturation with respect to calcium carbonate (Hem, 1992).

For the entire basin the range of calcium is from 2.8 mg/L (H38/0025) to 32.0 mg/L (I37/0013). The wells with the higher calcium concentrations are located near or within bedrock highs (I37/0009, I37/0013, I38/0014, I380015, I38/0053, and I39/0004). However, this trend is not seen in I38/0004 which has been drilled into bedrock, where the dominant cation is sodium taking up 79% of the cation concentration. There is a similar calcium/magnesium/sodium ratio for wells I38/0003 (48m) (alluvial fan), I38/0014 (23.95m) (alluvial fan), I38/0053 (8.9m) (alluvial fan), I38/0054 (6m) (Mary Burn), and H38/0063 (48m) (moraine).

In the Twizel sub-basin, calcium is dominant with magnesium and sodium present in much lower quantities, in comparison to the Tekapo sub-basin. None of the samples have equal levels of calcium and magnesium present (which would be the case if dolomite was present). This could possibly be due to the close proximity of the metamorphosed region in the west of the basin, where many of the wells in the Twizel sub-basin are recharged from surface water flows. Hem (1992) notes that rivers in more arid regions where soluble source rocks are exposed tend to have much higher dissolved calcium concentrations.

4.4.2 Magnesium

Magnesium can be derived from chlorite, hornblende, pyroxene, and olivine. The main source of magnesium in New Zealand aquifers is silicate as dolomite aquifers are rare (Rosen, 2001). If dolomite was present calcium and magnesium should have a 1:1 relationship (Hem, 1992), which is not the case within the study area. The range of magnesium within the basin is from 0.32 mg/L (H38/0025) to 7.1 mg/L (I38/0014). Overall, the Tekapo sub-basin has a higher content of magnesium in comparison to other cations. In a similar way to calcium, higher levels of magnesium concentrations are located near bedrock highs (I37/0013, I38/0003, I38/0014, and I38/0053). However, this trend is not seen in I38/0004 which has been drilled into bedrock.

4.4.3 Sodium

Sources of sodium include halite, sea spray, hot springs, brines, and some silicates including plagioclases albite and nepheline. Most sodium is the result of natural ion exchange, where montmorillonite clay reacts with magnesium and calcium and releases sodium (Hounslow, 1995). The only sink for sodium is reverse ion exchange; however this is uncommon in New Zealand groundwaters (Rosen, 2001). Generally, when sodium has been brought into solution it tends to remain in solution as there are no significant precipitation reactions that can reduce the sodium concentration in water (Hem, 1992).

In New Zealand groundwater most of the sodium and chloride is derived from the ocean. However, in other areas sodium may be enriched relative to chloride due to water-rock interaction, for example, with sodium feldspars or ionic exchange with clays (Rosen, 2001). Potassium feldspars are fairly resistant to weathering, however species containing sodium and calcium are more susceptible to weathering and yield the cations and silica to solution and, in conjunction with aluminium, form clay minerals (Hem, 1992).

The range of sodium concentrations within the Mackenzie Basin is 1.4 mg/L (all three lakes) to 55 mg/L (I38/0004). Overall the Tekapo sub-basin has higher concentrations of sodium compared to the Twizel sub-basin. There is no correlation of sodium levels to well depth. Within the basin sodium is enriched relative to chloride and this is probably due to the weathering of sodium feldspars or ionic exchange with clays as suggested by Hounslow (1995) and Rosen (2001). There does appear to be higher concentrations of sodium in wells that are located close to bedrock highs. There is one anomalous well (I38/0004) that has 79% of cation concentration being attributed to sodium. This is likely to be due to the well being drilled into bedrock and as a result the groundwater in the well has a long residence time. This well also has the highest level of total dissolved solids (260 mg/L) and this correlates with a long residence time giving rise to increased water-rock interaction (weathering) of feldspars within the greywacke/Torlesse sandstone bedrock.

4.4.4 Potassium

The source of potassium is generally from potassium feldspar, mica particles, and illite or other clay minerals. The common sinks for potassium are plant uptake and ion exchange reactions that form clays (Hem, 1992; Hounslow, 1995; Rosen, 2001). Potassium can become available for re-solution when plants mature and die, or when leaves shed at the end of the growing season; this potassium is leached into the soil by rains during decay of organic material and some leakage to the groundwater system would be expected (Hem, 1992).

Potassium ranges from 0.3 mg/L (H38/0021) to 13.0 mg/L (I37/0009). There is no correlation of potassium levels with well depth. Overall, the Tekapo sub-basin has a slightly higher concentration of potassium compared to the Twizel sub-basin, and this could be due to the location of wells within the Twizel sub-basin which are in areas with greater vegetation where plant uptake of potassium provides a large sink. Rosen (2001) notes that low concentrations of potassium are common as it is easily removed from solution during reactions within the soil zone or aquifer. Another possibility is that the Twizel sub-basin groundwater is being recharged by surface flows and therefore is ‘flushing’ through the system faster than the Tekapo sub-basin.

The anomalous sample is from I37/0009 (13.0 mg/L) which is located in a fairly swampy area west of Lake Tekapo. When comparing the sample collected in 2007 with the 2005 sample there is quite a large variance and could be due to increased flow rates of streams flowing into the swamp area in 2007 resulting in soil leaching by runoff. Rainfall (and therefore stream flows) in the area is generally higher in spring months (October) compared to summer months (March). However, this is the only sample that shows this variation between the two years and another sample should be taken to confirm the variance between the two samples.

4.5 MAJOR ANIONS

4.5.1 Bicarbonate (Alkalinity)

Alkalinity of a solution is measured by the capacity of the solution to neutralise an acid (Hem, 1992). The main components that buffer pH and contribute to alkalinity are carbonate (CO_3), bicarbonate (HCO_3), and carbonic acid (H_2CO_3) (Hounslow, 1995). Most alkalinity in groundwater is due to the amount of inorganic carbon ions present in solution, and therefore provides a measurement of bicarbonate or carbonate in solution (Deutsch, 1997). Generally, bicarbonate is the main contributor of alkalinity to water with a pH between 4.5 and 8.3. There are several sources of bicarbonates and carbonates such as reactions with water and CO_2 in the atmosphere, sulphate reduction, and from the dissolution of carbonate rocks (calcite, aragonite, dolomite) (Rosen, 2001). The precipitation of calcite is the most common sink of bicarbonate.

Within the study area, alkalinity ranges from 13 mg/L (H38/0025) to 145 mg/L (I38/0004). Figure 4.9 (see Appendix 4B) shows the geographical distribution of alkalinity throughout the entire basin. Alkalinity is higher within the Tekapo sub-basin, and is highest in wells with a depth close to or within the bedrock at Mt John and the Rollesby Range. The exception is I38/0052 with a fairly low alkalinity of 39 mg/L. It is likely that alkalinity is lower here as the groundwater is shallow, flowing within the alluvial fans on the side of the Rollesby Range. Within the Tekapo sub-basin there is a strong correlation with increasing total dissolved solids and conductivity with increasing alkalinity, suggesting a long residence time of water within the Tekapo sub-basin. However, there is no apparent relationship of alkalinity to well depth, suggesting that the alkalinity concentrations are an indication of the recharge source.

Within the Twizel sub-basin alkalinity levels are low, especially in those wells located within the riverbeds of surface streams, where groundwater is recharging downwards through infiltration of surface water flows. Similar alkalinity levels are seen in all three lakes. Within the Twizel sub-basin the deeper wells do have slightly higher levels of alkalinity.

4.5.2 Chloride

Generally chloride is derived from halite dissolution or from the ocean via rainfall, in the form of sodium chloride (Hounslow, 1995). The dominant source of chloride in New Zealand is from salts carried by rainfall (Rosen, 2001). When comparing hydrogeological studies throughout the Canterbury Plains with the Mackenzie Basin (Table 4.1), the concentration decreases quite significantly when moving inland away from coastal areas.

The concentration of chloride within the basin is very low and ranges from 0 mg/L (H38/0188) to 4.2 mg/L (I38/0003). There is no correlation of chloride concentrations with well depth. There is generally a higher concentration within the Tekapo sub-basin and this is probably due to enrichment of rainfall with respect to chloride as it passes through the soil surface. Figure 4.10 (see Appendix 4B) indicates the distribution of chloride levels within the basin, and shows that concentrations are higher in the southeast compared to the northwest of the basin. This suggests that the Tekapo sub-basin may be recharged by rainfall infiltrating through the surface, whereas the Twizel sub-basin is recharged by surface waters which move through the soil profile quickly. There is also a trend of increasing ion concentration with increasing chloride levels which would also suggest that this area is recharged by rainfall as there is less river water to dilute enriched rainfall within the Tekapo sub-basin. This trend is seen in wells I38/0003, I38/0004, I38/0053, I38/0014, I38/0015, I39/0004, I39/0007, and I37/0013.

4.5.3 Sulphate

Sulphate in groundwater is usually derived from the oxidation of pyrite, the dissolution of gypsum and anhydrite, or sea spray (Rosen, 2001). Under some conditions organic sulphur compounds can contribute to sulphate concentrations (Hounslow, 1995).

Within the Mackenzie Basin, sulphate concentrations range from 0.5 mg/L (H38/0063) to 31 mg/L (I38/0004). There is no decrease of sulphate levels with well depth, which would be expected if sulphate reduction was occurring at depth. Overall, sulphate levels are higher in the Tekapo sub-basin compared to the Twizel sub-basin, indicating that either reducing conditions are more prevalent in the Twizel sub-basin or that the minerals are not available for oxidation or dissolution to produce sulphate. Rosen (2001) notes that increased sulphate concentrations can also occur where fertiliser (gypsum) has been applied.

4.5.4 Nitrogen (Nutrients)

In groundwater nitrogen can be measured in several forms, and for this study both nitrate (NO_3) and ammonia (NH_4) have been measured. In groundwater where oxygen is abundant, nitrate nitrogen is usually the stable form, and ammonia nitrogen is present in oxygen depleted groundwater (Close *et al.*, 2001). In New Zealand the source of nitrogen is predominantly from anthropogenic sources. Nitrogen from untreated human waste water is either in the form of ammonium or organic nitrogen, while chemical fertilisers contribute ammonium or nitrate nitrogen (Close, *et al.*, 2001). Grazing animal waste contributes urea which is converted to ammonium nitrogen through hydrolysis or decomposition. Nitrate nitrogen from rain, igneous rocks, dissolution of nitrate minerals, or from deep geothermal fluids is rare in New Zealand (Close, Rosen, & Smith, 2001).

The nitrate levels from the 2007 samples are shown in Figure 4.11. The nitrate levels from the earlier 2005 samples are shown in Figure 4.12. In 2007, for those wells with a detectable level (>0.09 mg/L), the range of nitrate nitrogen ranges from 0.1 mg/L (H38/0021, H38/0025, H38/0057, and I38/0052) to 1.6 mg/L (I38/0003). All levels are well below the current New Zealand drinking water standards (see Appendix 4C**)** (Ministry of Health, 2005). When comparing the two sets of samples, the level of nitrate nitrogen has decreased in well H38/0025, whereas I38/0003 has over double the concentration in 2007 compared to 2005. However, when comparing the Mackenzie Basin nitrate nitrogen concentrations with the Canterbury Plains area, where the average levels range from 3.1 to 5.2 mg/L, they are very low. Even the Wanaka Basin has higher concentrations with an average of 2.4 mg/L and a maximum value of 42 mg/L, which are attributed to agricultural practices within the area (Table 4.2). The Mackenzie Basin has a very low population and land use is predominantly low intensity pastoral farming. The sample with the elevated level is likely to be due to farming practices in that area or due to natural seasonal variations as the water table falls and rises. Overall there have been five increases and two decreases in nitrate nitrogen levels between the 2005 and 2007 samples (refer to Table 4.5 in Appendix 4B).

Ammonium Nitrogen was also sampled in 2007 and concentrations ranged from 0.008 mg/L (I38/0052) to 0.18 mg/L (I38/0015). As noted by Rosen (2001) a negative correlation can be seen between nitrate and ammonium nitrogen; as ammonium nitrogen increases nitrate nitrogen decreases, because ammonium is the oxidised form of nitrate and occurs under increasingly anaerobic conditions. Ammonium nitrogen is more detrimental than nitrate nitrogen to both the environment and human and animal health (Rosen, 2001). The sample with a higher ammonium concentration (I38/0015) does not appear to have comparative reducing conditions (sulphate is present and dissolved oxygen has an average level), however when the well was sampled it did have a sulphuric smell. In comparison to nitrate ions ammonium ions are readily adsorbed onto some clay minerals which could reduce its concentration in solution (Hounslow, 1995).

4.5.5 Reactive Phosphorus

In New Zealand the most common source of phosphorus is pollution from fertiliser use in agricultural areas (Rosen, 2001). Phosphorus is generally taken up by organic matter or will adsorb onto clay particles, therefore making its mobility fairly low (Rosen, 2001). High levels of calcium, iron, or aluminium will also reduce phosphorus solubility.

Within the basin, samples with detectable levels of phosphorus range from 0.0011 mg/L (Lake Tekapo) to 0.032 mg/L (H38/0063). A comparison of phosphorus levels between 2005 and 2007 cannot be made as groundwater was not analysed for this element in 2005. Generally, the 2007 results show that there are higher levels of phosphorus in the Twizel sub-basin and this could be due to more intensive agricultural practices and fertiliser application being carried out within this area. Another possibility is that the higher concentrations of calcium ions present in the Tekapo sub-basin are reducing phosphorus solubility within the area.

4.6 TRACE METALS AND NON METALS

4.6.1 Iron and Manganese

If large quantities of dissolved oxygen are present in groundwater, iron and manganese will generally not be dissolved in solution. Generally, anoxic and reducing conditions are needed before appreciable levels of dissolved iron and manganese are detected (Hounslow, 1995). In New Zealand, iron is generally only detected in relatively slow moving groundwater where oxygen is consumed by reactions with organic matter or other chemicals (Rosen, 2001).

All samples had no detectable level (<0.01 mg/L) of manganese present. All but three samples had no detectable level (<0.03 mg/L) of iron present. The samples that did have detectable levels of iron present were H38/0063 (0.035 mg/L), H38/0021 (0.059 mg/L), and H38/0059 (0.069 mg/L). These levels of iron are still very low; Hem (1992) notes that iron levels ranging from 1.0 to 10 mg/L are common.

4.6.2 Boron

Boron is a major constituent of the mineral tourmaline and generally occurs in an unweathered state in sandstones (Hounslow, 1995). It is also present in seawater, and can be removed by adsorption onto clay minerals (Hounslow, 1995).

Of all the 21 samples analysed only seven had detectable levels of boron. The concentration ranged from 0.01 mg/L (H38/0059, I38/0003, I38/0015) to 0.64 mg/L (I38/0004). Of the seven samples, five were located in the Tekapo sub-basin close to bedrock highs. The two samples in the Twizel sub-basin are within approximately 100 metres of each other with similar depths located in an area mapped as glacial till.

4.6.3 Fluoride

The source of fluoride is often from fluorite, apatite, or fluoride-bearing micas and amphiboles (Hounslow, 1995). Generally, the concentration of fluoride in fresh water is < 1 mg/L (Hem, 1992), and in most New Zealand wells is <0.5 mg/L (Rosen, 2001). Adsorption of fluoride onto clay minerals (kaolinite, gibbsite, and halloysite) via ion exchange generally occurs when the pH is 6.0 and desorption occurs below pH 4.0 and above pH 7.5, resulting in alkaline waters often being high in fluoride (Hounslow, 1995; Rosen, 2001).

Fluoride is detectable in four wells: H38/0188 (0.074 mg/L), I38/0053 (0.12 mg/L), I38/0015 (0.5 mg/L), and I38/0014 (1.1 mg/L). Two of these wells indicate that desorption is occurring indicated by high alkalinity with a pH above 7.5 (I38/0004 and I38/0015). There is an indication that the bedrock is possibly contributing to fluoride concentrations.

4.6.4 Aluminium

Aluminium is abundant within silicate igneous rock minerals (feldspars, feldspathoids, micas, and amphiboles) and sedimentary aluminium enriched minerals such as clays, however it rarely occurs in solution in natural water in concentrations greater than a few tenths to hundredths of a mg/L, and when present is usually due to water with a low pH (Hem, 1992).

Aluminium is detectable (>0.006 mg/L) in five samples and range from 0.014 mg/L (I38/0052) to 0.047 mg/L (I38/0015). All samples with detectable levels are located within the Tekapo sub-basin. Such low concentrations could represent particulate material within the sample, as suggested by Hem (1992).

4.6.5 Reactive Silica

Silica is very abundant in the earth's crust and is a major constituent of grains in most sandstones in the form of quartz. At lower water temperatures silica is primarily derived from silicate weathering (Hounslow, 1995). Quartz is highly resistant to weathering and therefore the amount of silica available for solution will be less. The silicate mineral potassium feldspar ($KalSi_3O_8$) is more susceptible to weathering and therefore silica is available for solution from this mineral source. Rosen (2001) suggests that at concentrations <30 mg/L of both silica and sodium a correlation can be seen. A moderately strong correlation was found for the Tekapo sub-basin (R^2 = 0.6) where silica, in samples with concentrations <30 mg/L, increases with increasing sodium levels. This relationship is not as strong for the Twizel sub-basin. The correlation between silica and sodium levels at lower concentrations is likely to reflect the equilibrium dissolution of sodium feldspars and ion exchange reactions within the aquifers (Rosen, 2001). Higher concentrations of silica are often related to the type of rock and the temperature of the groundwater (Hem, 1992). Within the basin there is a small correlation of increasing silica concentrations with increasing water temperature.

The three lakes have the lowest concentrations of silica illustrating the young, rapidly flowing water moving from the lakes through the canal system. There is insufficient time for the water to interact with bedrock to bring silica into solution. Wells that are relatively shallow and close to active river beds have intermediate values of silica (7.9 to 8.5 mg/L), suggesting fast flowing water is passing through the groundwater system. The highest values of silica are found in wells located in the Mt John and Tekapo moraines, and the deep well (I38/0014 – 80.8 m) which is located in the Balmoral Outwash Gravels. The water flowing through these areas is slower moving and has greater residence times, therefore resulting in more water-rock interaction and bringing more silica into solution.

4.6.6 Arsenic

Several processes control the metal species present in groundwater including ion exchange and adsorption onto mineral surfaces, oxidation-reduction state of groundwater, formation of organic ligands, and pH. It is possible that preferential flow paths within an aquifer may allow for metals to be transported (Rosen, 2001). In other areas where glacial till is present, arsenic has been found to be associated with high values of iron, bicarbonate, and nitrate nitrogen in conjunction with low concentrations of sulphate, chloride and manganese. The availability of organic matter is the primary factor that determines arsenic solubility (Kelly *et al.*, 2005).

The groundwater was tested for arsenic levels and all but three samples had no detectable levels. Of the three, one well (H38/0059) was over the 2005 maximum acceptable value for drinking water (0.1 mg/L). Subsequently the adjacent well (H38/0188) was tested, but no arsenic levels were detected. The other two samples with detectable levels were Lake Ohau and well H38/0051. Both samples were within the drinking water standards.

It is suggested that the source of the arsenic is derived from arsenopyrite leaching from the schist rocks prevalent at the head of Lake Ohau and within the Ben Ohau Range which is less than 1 km to the north of well H38/0059. Given the similarity of the chemistry composition between Lake Ohau and H38/0051, it is likely that this well is encountering leakage from Lake Ruataniwha (Lake Ohau derived water) at depth and that this is the reason for a detectable level (0.02 mg/L) of arsenic within this well. Another possible source of arsenic is from hydrothermal calcite veins in the Main Divide region where high arsenic concentrations result from transport of arsenic-rich crustal fluids moving upward along fault zones (Horton *et al.*, 2001). The region that this may be occurring is much further to the northwest of the area, but given the source of water for Lake Ohau is from glaciers and high mountain ranges in the northwest it is possible that dilute concentrations of arsenic derived from fault zones could be moving through the system towards the southeast.

It is probable that H38/0059 had a higher level of arsenic as the pH (8.7), fairly low sulphate levels (2.1 mg/L), and dissolved oxygen level (0.1 mg/L) are conducive to arsenic mobilisation into solution. Although H38/0059 and H38/0188 have similar depths and are located 100 metres apart, it is possible that arsenic was not detected in H38/0188 as the well is used regularly (and had a pH of 7.7 and dissolved oxygen of 7.6 mg/L), whereas H38/0059 is not used for any purpose. It was initially thought that the well could be located at a site of an old sheep foot trough which could contribute to arsenic levels, but it was confirmed that this was not the case.

4.7 GROUNDWATER QUALITY

The results from the samples collected during February 2005 have been included here for comparison with the 2007 results and are shown in Table 4.3 (see Appendix 4B). Table 4.4 (see Appendix 4B) summarises the results of the October 2007 chemistry analysis. For comparison and to identify trends, the results for wells sampled in both February 2005 and October 2007 are combined in Table 4.5 (see Appendix 4B). Of the 21 samples collected during 2007, seven samples exceeded the 2005 Drinking Water Standards of New Zealand aesthetic guideline value for pH (7.0 to 8.5), and one sample exceeded the Maximum Acceptable Value (MAV) for arsenic (0.01 mg/L). The samples that have exceeded the guide lines are highlighted in Table 4.4. The 2005 Drinking Water Standards of New Zealand are included in Appendix 4C.

4.7.1 pH

Potential Hydrogen (pH) refers to the amount of activity of free, uncomplexed hydrogen ions found in a solution and measures the ability of the environment to supply or remove hydrogen ions to the solution (Hounslow, 1995; Deutsch, 1997). The amount of free hydrogen ions present determines the acidity or alkalinity of the solution.

The range of pH for all samples was 6.1 to 9.5. Of the 21 samples taken in 2007, seven transgressed the Ministry of Health (2005) Drinking Water Standards for New Zealand (DWSNZ) aesthetic guidelines, which recommends that pH should be within a range of 7.0 to 8.5. Of the seven samples, four were more acidic (<7.0) (I38/0003, I38/0052, H38/0021, and H38/0025) and three were more alkaline (>8.5) (I37/0009, H38/0051, and H38/0059) than the Ministry of Health recommended limits.

Figure 4.13 (see Appendix 4B) indicates the distribution of pH within the Mackenzie Basin. There does not appear to be a correlation with depth. The general trend throughout the basin indicates that the slightly more acidic groundwater is from shallow wells located within the active river bed of the Twizel River along with two wells in the Tekapo sub-basin that are likely to deriving their water from alluvial fans. This could be an indication that these wells are being recharged by fresh rainfall which is slightly more acidic than groundwater that has had time to move through the subsurface. The more alkaline samples are from two deeper wells within the Twizel sub-basin close to Lakes Ohau and Ruataniwha. The highest pH level was measured in the Tekapo town water supply (I37/0009) with a value of 9.5. The sample well in 2005 had a pH of 6.9 indicating a dramatic increase towards alkaline water. The reason for such a large increase is not fully understood and requires further investigation. All three lake samples were fairly close to neutral with values ranging from 7.7 to 7.8, however the pH value is from the lab analysis as the pH of the lakes was not measured in the field. It is therefore possible that the lakes are actually slightly more alkaline than indicated.

The pH values can indicate different geochemical environments that the groundwater has been in contact with. Table 4.6 summarises different environments for different ranges of pH as suggested by Hounslow (1995).

The air in soil interstices has a high CO_2 content which is dissolved by water moving through the soil zone. The H, HCO_3, and CO_3 ions are strong forces controlling the pH of water and in the weathering of rock minerals (Hem, 1992).

Table 4.3: Variable environments giving rise to a range of pH values (modified from Hounslow, 1995).

pH Range	Environment	Result of Environment Type
Strongly Acid pH < 4	Acid geothermal waters Waters resulting from oxidation of pyrite (acid mine drainage) Acid rain	Clay minerals are destroyed Aluminium, Copper, and Zinc mobilises SO_4 > Cl and HCO_3 absent
Moderate Acid pH 4 – 6.5	Carbonic acid (a result of precipitation, solution of CO_2 from atmosphere or oxidation of organic material) Dissolved organic acids (from decaying organic matter, also common in podzolic soils)	Feldspars usually alter to clay minerals Some trace elements may mobilise
Neutral pH 6.5 – 7.8	Bicarbonate usually dominant ion Cations mainly Ca and Mg In dry climates caliche layer in soil and carbonate concretions possibly present Manganese often mobile as a bicarbonate	Na, K, Ca, Mg, Cl, SO_4, and HCO_3 are common and reflect composition of the rocks with which they are in contact
Moderately Alkaline pH 7.8 – 9	Often close to saturation with calcite Measurable carbonate (CO_3) present Silica often mobile	Carbonates precipitate Trace metals co-precipitate
Strongly Alkaline pH > 9	Rare under natural conditions, but occurs if Na, Ca, or Mg hydroxides are present Alkaline lake waters containing dominant Na, CO_3, and HCO_3 may form when alkalinity of surface water is greater than Ca and Mg content After precipitation of alkaline earth carbonates, the water contains Na as the cation and bicarbonate as the anion	Leaching of fresh cement may result when $Ca(OH)_2$ is present – reacts with other constituents to form calcium aluminosilicates (often observed in freshly cemented wells)

4.7.2 Total Hardness

Total hardness is the sum of calcium plus magnesium expressed as calcium carbonate, and is defined by the ability of water to create soap lather (Hounslow, 1995). Generally, it is more difficult to produce soap lather in harder water in comparison to soft water. Table 4.4 Table 4.7 indicates the degrees of water hardness.

Table 4.4: Classification of total hardness (Hem, 1992)

Hardness Range (mg/L of $CaCO_3$)	Description
0 – 60	Soft
61 – 120	Moderately Hard
121 – 180	Hard
> 180	Very Hard

The range of total hardness (calcium carbonate) is from 8 mg/L (H38/0025) to 95 mg/L (I37/0013). The Mackenzie Basin has predominantly soft water with only three wells being classified as moderately hard. There is no apparent correlation of hardness values with well depth. Figure 4.14 (see Appendix 4B) indicates that there is a general trend in spatial distribution with lower hardness values being present in the Twizel sub-basin, and higher values in wells close to bedrock areas where rainfall moving through fractures within the bedrock could be providing recharge for these wells.

All values of alkalinity are greater than total hardness indicating a temporary hardness water type. Temporary hardness is the calcium and magnesium carbonate that would be removed by boiling, leaving a precipitate of $CaCO_3$ (Hounslow, 1995).

4.7.3 Total Dissolved Solids

Total dissolved solids (TDS) are the solids that remain following evaporation of a water sample, and are calculated by adding the concentration of all the major ions along with silica (Hounslow, 1995; Fetter, 2001).

All samples have values less than 1,000 mg/L, indicating that all samples can be classified as fresh water. TDS ranges from 20 mg/L (Lake Ohau and Lake Pukaki) to 260 mg/L (I38/0004). The samples with comparatively higher levels of TDS are within the Tekapo sub-basin and are located close to bedrock hills (I37/0013, I38/0004, I38/0014, I38/0053) (Figure 4.15 – Appendix 4B).

The lower TDS values are in the Twizel sub-basin and, apart from the lake samples, are lowest in the wells in the active river bed of the Twizel River. There is a general trend within the Twizel sub-basin of increasing TDS with increasing well depth. The higher TDS values also indicate a longer residence time of water in contact with rock. The higher values closer to bedrock highs indicate that water is moving more slowly through these areas and thus has the opportunity for increased mineral reactions.

4.7.4 Conductivity

Conductivity is the ability of a substance to conduct an electrical current. Pure water has a very low electrical conductance. Conductivity will increase when ion concentrations within the water increase, therefore conductivity provides an indication of ion concentration (Hem, 1992). For the 2007 well samples, conductivity ranges from 3 mS/m (H38/0025) to 31.5 mS/m (I38/0004). The conductivity has a linear relationship with the total dissolved solids values throughout the basin. The highest values are located in the two wells that are in or very near to bedrock indicating longer residence times of the water in these wells (Figure 4.16 – Appendix 4B).

4.7.5 Dissolved Oxygen

The measurement of the dissolved oxygen content is an indication of the biochemical conditions of the water at a specific time and place. The level of dissolved oxygen will vary with changing temperatures and subsurface conditions. The solubility of oxygen in water is mainly controlled by pressure and temperature (Hem, 1992). Dissolved oxygen levels should be highest in water close to the surface and close to recharge areas. The source of oxygen within the water is from exposure to air, but can also be produced as a by-product of photosynthesis (Hem, 1992). As water moves through an aquifer from the recharge point to the discharge point, oxygen is consumed by organic matter that may be present and/or mineral interactions (Hounslow, 1995). As the oxygen is consumed the groundwater can become anaerobic and create a reducing environment where other elements may form.

The range of dissolved oxygen levels within the Mackenzie Basin is from 0.1 mg/L (H38/0059) to 10.4 mg/L (I38/0003). There is no strong correlation of dissolved oxygen with well depth; however, samples with the highest levels of dissolved oxygen are located in active riverbeds (H38/0024 and I37/0009) and close to alluvial fans (I38/0003). Samples with low dissolved oxygen levels are found in areas close to bedrock (I37/0013 and I38/0004), within moraine deposits (H38/0063), or within low permeability formations (H38/0059 and I38/0015). The distribution of dissolved oxygen levels is shown in Figure 4.17 (see Appendix 4B).

4.7.6 Sodium Adsorption Ratio

The Sodium Adsorption Ratio (SAR) is used to measure the degree to which sodium within irrigation water replaces the adsorbed calcium and magnesium in the soil clays which may cause damage to the soil structure (Hounslow, 1995). The change in soil structure can reduce the permeability of the soil when wet and increase hardness of the soil when dry. If the irrigation water is high in sodium and low in calcium and magnesium, the cation-exchange complex may become saturated with sodium (Fetter, 2001). To evaluate the hazard of high sodium water the following equation is used (units expressed in meq/L):

$$\boxed{SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}}$$

Using this equation the hazard resulting from sodium adsorption can be defined as shown in Table 4.8. The lower the ionic concentration of the solution, the higher the sodium hazard is for a given SAR (Fetter, 2001).

Table 4.5: Classification of sodium hazard of damage to soil structure obtained from the sodium adsorption ratio (Fetter, 2001).

Sodium Adsorption Ratio	Level of Hazard
2 – 10	Low hazard
7 – 18	Medium hazard
11 – 26	High hazard
> 26	Very high hazard

For all samples except one, the SAR is less than 1 indicating that soil structure damage from sodium enriched irrigation water is unlikely. The SAR values are indicated on Table 4.3 and Table 4.4 (see Appendix 4B). The one sample that is above 1 is I38/0004 and has a SAR of 4.4 indicating that the hazard is low.

4.8 GROUNDWATER CLASSIFICATION

The composition of groundwater can be influenced by aquifer material, residence times, flow rates, recharge sources, and contamination. There are several graphical methods that can be used to describe the relative concentrations and variability of anions and cations in water samples. A number of methods have been used to illustrate the 2005 and 2007 data previously discussed in this chapter. The two most common types of plots have been used for ease of comparison with data from other regions such as the Canterbury Plains.

4.8.1 Stiff Plot

A simple method to display groundwater chemistry data is the use of Stiff plots. These allow chemistry patterns and relationships between groundwater samples to be graphically identified. Stiff plots use the milliequivalent values of the four major anions and four major cations. These values are plotted to the right and left of a vertical axis and create irregular shapes. The size of the shape is relative to the total ion concentration. The pairs used in this study for the Stiff plots are Ca and HCO_3, Mg and SO_4, Na + K and Cl, Fe and NO_3.

The results have been divided into sub-basins and have been plotted relative to the depth of the well. Figure 4.18 illustrates the results for 2007 and Figure 4.19 illustrates the results for the same wells that were sampled in 2005 for comparison. The plots illustrate the much higher ion concentration within the Tekapo sub-basin compared to the Twizel sub-basin, indicating that the groundwater is moving along flow paths within the subsurface at a faster rate in the Twizel sub-basin. A general trend of increasing ion concentration with increasing well depth is apparent in the Twizel Sub-basin. The Tekapo sub-basin appears more variable, and there is no real trend of ion concentration with depth, possibly indicating the variable lithology types that each of the wells are located within. When comparing the 2005 and 2007 results, it can be seen that generally the wells in the Tekapo sub-basin have increased over time where as some of the wells in the Twizel sub-basin have decreased in ion concentration between the two years. It also shows that wells H38/0051, I39/0004, and I39/0007 have all had an increase of calcium and a decrease in sodium over the two year period.

4.8.2 Piper Diagram

Another graphical method is the Piper diagram which can be used to plot multiple samples to evaluate the hydrochemical facies of the groundwater region. The Piper plot can also be useful to indicate whether groundwater may be the result of a mixing of waters or has been affected by solution-precipitation reactions (Loris, 2000). The other benefit of using a Piper diagram over a

Stiff plot is the ability to plot a large number of data on a single graph so that major groupings of hydrochemical facies can be discerned visually (Freeze & Cherry, 1979). The Piper diagram is a trilinear plot using the percentages of the major cations and anions in milliequivalents per litre. The Piper diagram was modified by Back (1960) to include triangles indicating hydrochemical facies. Piper diagrams can be used to describe the nature of the water sample and the relationship between water samples. This allows water samples to be characterised and to differentiate geochemical signatures or trends present across samples. If samples group together on a Piper diagram, this can suggest a common composition and a common origin of the groundwater. This plot can give some indication as to the water type, but silica is not taken into consideration when viewing the results (Hounslow, 1995). The diamond section of the diagram is used to differentiate water types.

Results which plot near the left of the diamond are high in calcium and magnesium as well as bicarbonate, where the water has temporary hardness, which is the case for nearly all results within this study. One sample (I38/0004) plots in the area composed of alkali carbonates (Na + K and HCO_3 + CO_3), which is due to the high sodium content of this sample. Some of the samples plot on the corner of the anion triangle possibly indicating that these samples are precipitating calcium and bicarbonate. This can be confirmed with the mass balance technique (see Appendix 4D), which suggests that H38/0051, H38/0059, and I39/0004 are super saturated with respect to calcite. Both the Stiff plots and the Piper diagram confirm the dominance of Ca-HCO_3 type waters which are relatively young. This type of water chemistry is common in New Zealand groundwater and reflects the greywacke lithology present within the basin.

4.8.3 Equivalence Method

A non graphical method of hydrochemical facies has been used by Rosen (2001) to define the principal water types throughout New Zealand. The equivalence method uses milliequivalent values of the major cations and anions. These are converted to percentages and the ions are then listed, using concentrations greater than 10%, in decreasing order (cations first). Using this method the most common single water type is Ca-Na-HCO_3 followed closely by Ca-HCO_3. The results from this study have a similar trend, shown in Table 4.9. All but one sample is dominated by calcium and all wells are dominated by bicarbonate.

The Stiff plot and equivalence methods have also been combined and plotted geographically to determine if there are any spatial trends with regard to the hydrochemical facies (Figure 4.20). Flow patterns and directions can be interpreted by mapping hydrochemical facies and zones.

The differences in flow directions using this method can indicate changes in hydraulic conditions such as recharge rates (Glynn & Plummer, 2005). It can be seen that many of the facies defined using the equivalence method are located in similar regions or similar lithological areas. For example, the majority of the Ca-Na-HCO_3 type waters are located within the Twizel sub-basin, within or near the active river bed of the Twizel River. H38/0059 and I38/0015 are the exceptions, and this could be related to water being sourced from subsurface flows of rivers and streams flowing in the north.

The three lake samples and well H38/0051 all have the chemistry Ca-HCO_3 indicating that H38/0051 derives its water from lake leakage. Well I37/0013 also has the same chemistry as the lakes and could possibly be derived from lake leakage.

Within the centre of the basin, near the Mary Range and southeast towards the Grampian Mountains, the water type is predominantly Ca-Mg-Na-HCO_3. It is suggested that this water type is from groundwater that has had a longer residence time which has changed the chemistry of these samples or that mixing of recharge sources is creating this particular type of water (I38/0003, I38/0014, I38/0053, I38/0054).

The wells located within the moraines (H38/0038, H38/0063) have a water type of Ca-Na-Mg-HCO_3. H38/0057 and H38/0188 also have a similar chemistry suggesting that they may be encountering a similar lithology at depth as the wells within the moraines, or that they have similar recharge sources.

I38/0052 located in the alluvial fan near the Rollesby Range also has the water type Ca-Na-Mg-HCO_3, and is most likely to have a similar recharge source to the other four wells with this chemistry type, as the lithology at depth is unlikely to be similar as the alluvial fans sit on top of greywacke bedrock.

Wells I37/0009 and I38/0004 each have their own distinct water types. I37/0009 (Ca-Na-K-HCO_3), located in a swampy area near Fork Stream, shows a high potassium content. The source of the high concentration of potassium is unknown.

I38/0004 (Na-HCO_3-SO_4) is located within the bedrock of the Grampian Mountains and the water type is most likely derived from very slow moving recharge flows and a high degree of water-rock interaction which provides a large percentage of sodium.

Table 4.6: Hydrochemical facies using the equivalence method used by Rosen (2001).

Well Number & Lake Location	Well Depth (m)	Sub-basin	Hydrochemical Facies
H38/0032	2.85	Twizel	$Ca\text{-}Na\text{-}HCO_3$
H38/0025	4.5	Twizel	
H38/0004	11.4	Twizel	
H38/0021	12.2	Twizel	
I39/0007	18	Twizel	
H38/0059	53	Twizel	
I39/0004	68	Twizel	
I38/0015	80.8	Tekapo	
H38/0035	113.4	Twizel	
Lake Ohau	-	Twizel	$Ca\text{-}HCO_3$
Lake Pukaki	-	Twizel	
Lake Tekapo	-	Tekapo	
I37/0013	22	Tekapo	
H38/0051	41	Twizel	
I38/0052	2	Tekapo	$Ca\text{-}Na\text{-}Mg\text{-}HCO_3$
H38/0188	36	Twizel	
H38/0038	36.2	Twizel	
H38/0063	48	Twizel	
H38/0057	66	Twizel	
I38/0054	6	Tekapo	$Ca\text{-}Mg\text{-}Na\text{-}HCO_3$
I38/0053	8.9	Tekapo	
I38/0014	23.95	Tekapo	
I38/0003	48	Tekapo	
I37/0009	6	Tekapo	$Ca\text{-}Na\text{-}K\text{-}HCO_3$
I38/0004	28	Tekapo	$Na\text{-}HCO_3\text{-}SO_4$

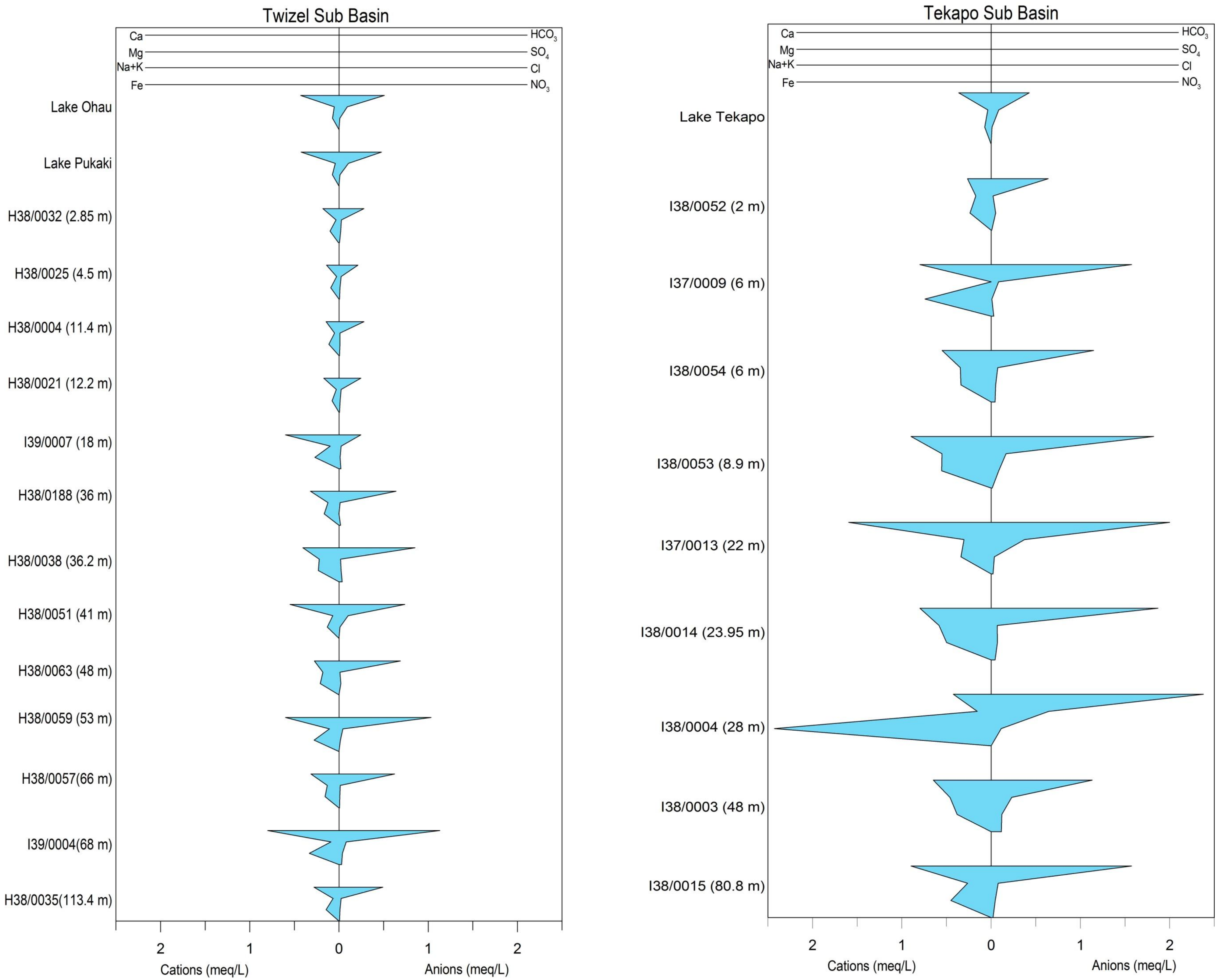


Figure 4.18: Stiff plots relative to well depth for 2007 results.

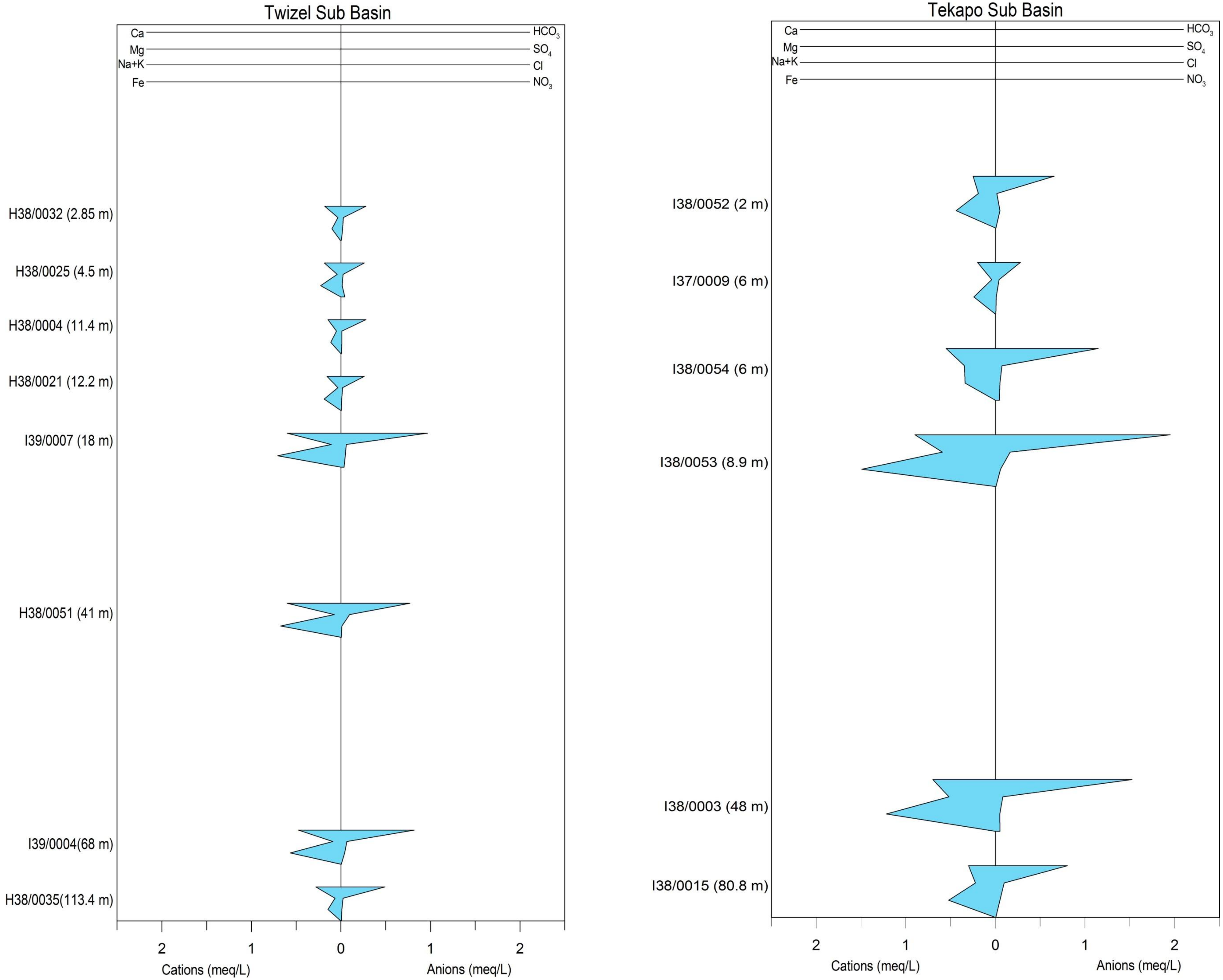


Figure 4.19: Stiff plots relative to well depth for 2005 results. The plot area is the same as the 2007 results for comparison purposes.

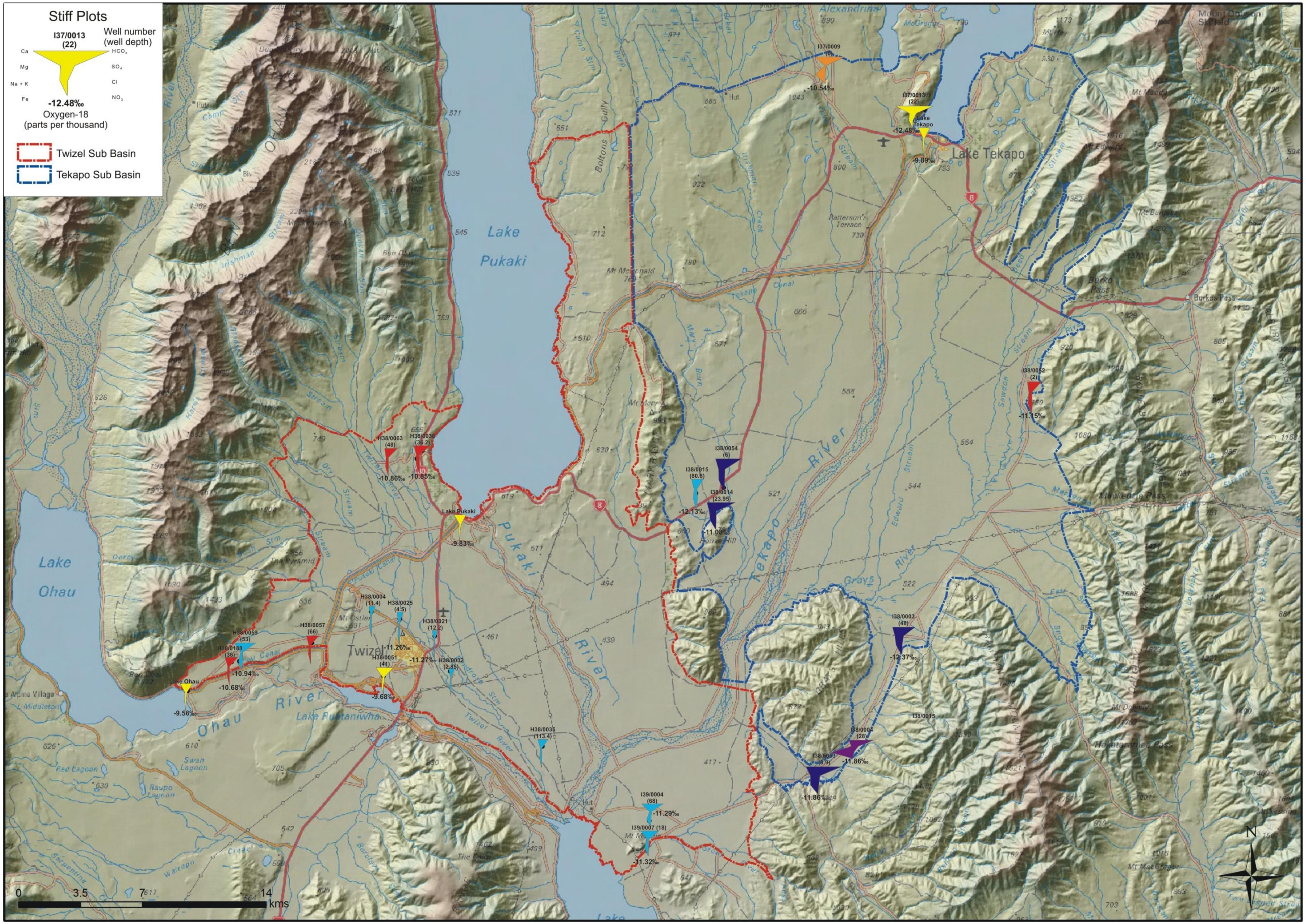


Figure 4.20: The use of Stiff plots coloured using the equivalence method have been plotted geographically to define any spatial distribution of the hydrochemical facies. .

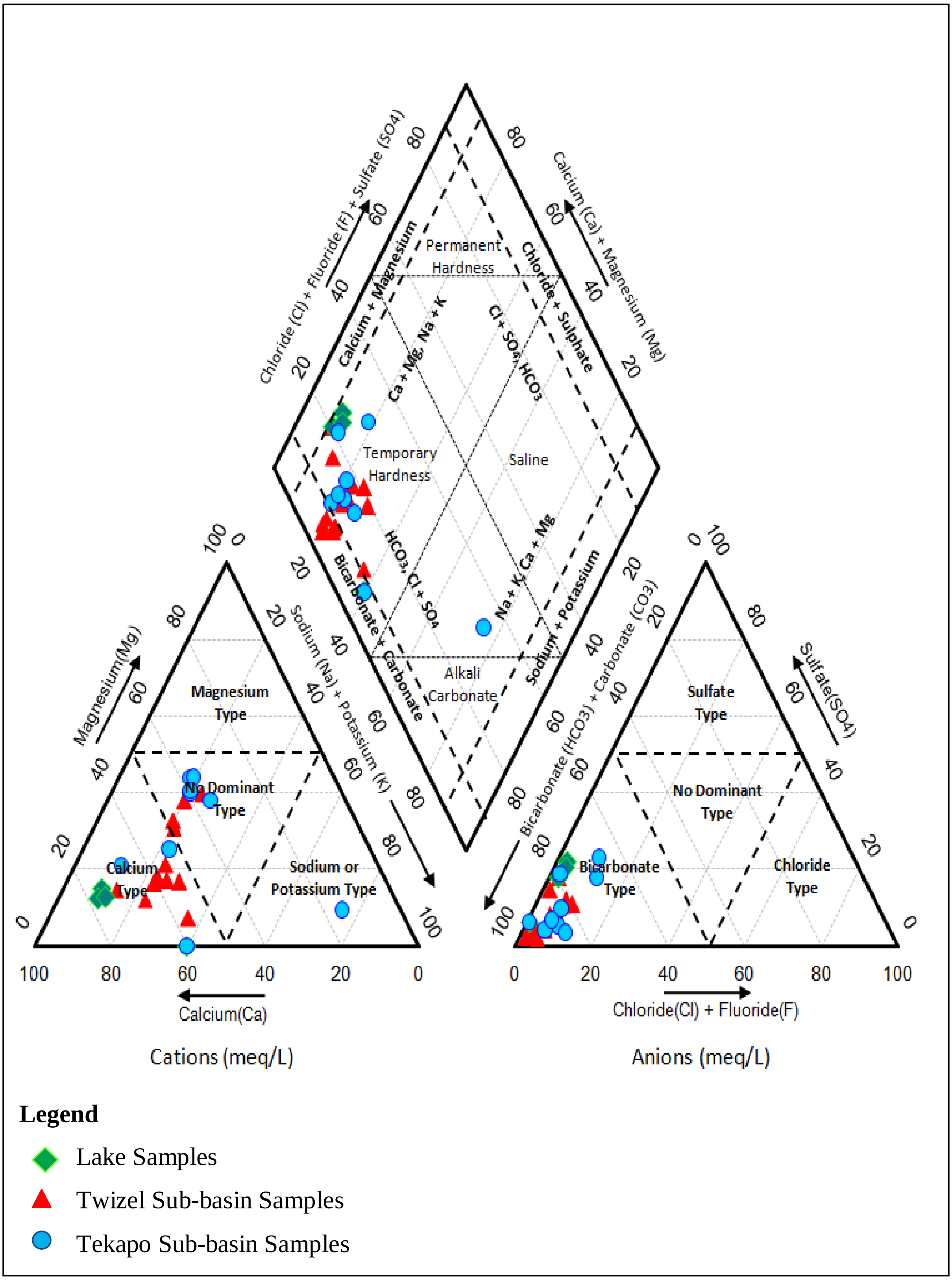


Figure 4.21: Piper diagram for lake and well samples taken in 2007.

4.9 WATER-SOURCE ROCK INTERACTION

Other hydrogeological studies on the Canterbury Plains have determined that there is no major variation of lithology affecting aquifers and that the Plains are dominated by greywacke sediments (Vincent, 2005). Within the Mackenzie Basin, the source rock lithology should be taken into consideration when interpreting water chemistry data. As discussed in Chapter Two, the area is surrounded by argillite and Torlesse sandstone in the east, and metamorphosed Torlesse and schist towards the west. The glacial sediments that fill the basin are derivatives of both of these sources.

Torlesse sandstones have been studied throughout the South Island and the lithology of the sandstone has been defined using XRF analyses. Mackinnon (1983) notes that the Torlesse sandstone has an average quartz:feldspar:lithic composition ratio of 29:47:24. The ratio of plagioclase to potassium feldspar is 5:1. Rock fragments are dominated by silicic volcanic, and quartzofeldspathic sandstone, mudstone, and schist are also present (Mackinnon, 1983). The Torlesse terrane contains an abundant amount of K-feldspar in the protolith granitic sandstone (Rosen & Jones, 1998). The XRF analyses indicates the percentage of minerals present and are listed in Table 4.10, this confirms the high content of silica present within the sandstone. Such a high content of the non ionic silica results in low silica and ion interactions (Vincent, 2005).

Table 4.7: XRF analysis data for the Torlesse Sandstone from the Permian and Mid Triassic. The percentage values are averages from 30 samples - 3% is due to loss on ignition (data from Mackinnon, 1983).

Mineral	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3T**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**
Percent	68	1	14	4	0	1	2	4	3	0

The basement rock of the Mackenzie Basin region has been described by Cox & Barrell (2007). The Tekapo sub-basin is surrounded by greywacke and is described as well indurated, greywacke sandstone with argillitic mudstone/siltstone and conglomerates present. This lithology outcrops at Mt John, the Mary Range, the Rollesby Range, and the Grampian Mountains. In comparison the Ben Ohau Range is mainly comprised of semi-schists and is described as a slightly foliated or cleaved greywacke sandstone and argillitic mudstone with low grade meta-tuff and meta-chert present. The change in composition from one side of the basin to the other can contribute to the variability in major ion concentrations present between the two sub-basins.

Generally the groundwaters of New Zealand have a greater proportion of bicarbonate compared to calcium, suggesting that bicarbonate is likely to be derived from reactions involving soil organic matter than from calcite dissolution (Rosen, 2001). However, in more arid regions, such as Central Otago, precipitation of calcite is likely (Rosen & Jones, 1998). When calcite dissolution controls the groundwater chemistry then calcium and bicarbonate will fall on a 1:1 line on a milliequivalent basis. Rosen & Jones (1998) suggested that the dissolution of calcite from the Otago Schist is the likely mechanism for producing calcium and bicarbonate on a 1:1 basis. The weathering of plagioclase feldspar (anorthite) will also produce the same 1:1 correlation; however, anorthite is much less soluble under New Zealand conditions and is not considered a major source of calcium and bicarbonate (Rosen, 2001).

A similar correlation can be seen within part of the study area (Figure 4.22 – Appendix 4D). The higher concentration of calcium present in the Twizel sub-basin is possibly being derived from schist bedrock present to the west and within the Ben Ohau Range to the northwest, in a similar way to the Wanaka Basin (but to a lesser extent). The correlation of $Ca:HCO_3$ is below the 1:1 line as shown in Rosen & Jones (1998) (Figure 4.23 – Appendix 4D), but the R^2 value for the Twizel sub-basin samples is 0.76 which is still a strong correlation. It should be noted, that the sample size for this suggestion (n=12) is much lower than that of the Rosen & Jones (1998) and may not be as relevant, statistically speaking.

Within the Tekapo sub-basin groundwater chemistry composition is similar to that found in the upper Canterbury Plains area as the source rock material is the same. The calcium present in this sub-basin is likely to be coming from the weathering of feldspars present in the greywacke.

The source rock type can also be suggested by comparing the Mg/Ca ratio to the silica content in mg/L (Figure 4.24 – Appendix 4D). There is an indication that the groundwater within the Tekapo sub-basin has a longer residence time to bring silica into solution, or that the sediment within the Tekapo area has undergone more weathering. The wells located in the active river bed of the Twizel River and the lake samples are useful to indicate that short residence time of water results in low silica content. Overall there does not seem to be a correlation with the depth of the well or the age of the groundwater with the Mg/Ca ratio or silica content. The Tekapo sub-basin samples have a higher Mg/Ca ratio than those of the Twizel sub-basin. As the ratio approaches one there is a suggestion that de-dolomitization may be occurring. To further compare the source rock type for groundwater interaction, the mass balance technique has been used along with the Debye-Hückel Equation to define saturation with respect to calcite. These results are located in Appendix 4D.

4.10 CHAPTER SUMMARY

During 2007 21 water samples were collected for analysis for a number of parameters for the purposes of defining the groundwater chemistry and groundwater quality. In 2005 wells were also sampled as part of the annual water quality investigation conducted by Environment Canterbury and the results from these samples have been included for comparative purposes.

The groundwater throughout the basin is predominantly a Ca-Na-HCO_3 type water. Calcium is the dominant cation and bicarbonate is the dominant anion. The water chemistry is typical of New Zealand groundwaters and is relatively young as it has not progressed through the Chebotarev sequence.

The three lakes that were sampled had their own distinctive water chemistry and this is also seen in one well suggesting lake leakage at depth in this area. Two other wells had distinctive chemistry also. One well in the north of the Tekapo sub-basin had a high percentage of potassium present. When comparing the results of 2005 and 2007 for this well they are very different suggesting that something has changed within the environment or that the sample should be re-analysed to confirm the results. Another well on the east side of the Tekapo sub-basin is dominated by sodium and it is thought to be the result of older groundwater moving slowly through the bedrock area.

The total dissolved solids (TDS) values for each sub-basin are distinctive and suggest that the Tekapo sub-basin has a slower moving groundwater system compared to the Twizel sub-basin giving rise to higher total dissolved solids values. The Twizel sub-basin appears to be recharged by fast moving surface waters and ion concentrations in this area are very low.

A number of other parameters have been analysed, and show that levels of many of the water quality determinands such as chloride and nitrate nitrogen are very low when compared to other areas such as the Canterbury Plains. The nitrate nitrogen levels are so low that they will be useful as a future monitoring parameter for groundwater quality. The very low levels of nitrate nitrogen could be used as a baseline to compare against as farming practices change in the future.

The heavy metal arsenic was found to be present in two wells and in Lake Ohau. One well had levels above the New Zealand Drinking Water Standards 2005, and the neighbouring well was subsequently sampled. This second well did not have any detectable levels of arsenic present. It is thought that the arsenic may be derived from leaching of arsenopyrite.

The data collected have been presented using graphical and non graphical methods. The Stiff plots and Piper diagram confirm the dominance of a Ca-HCO_3 ions and the difference in ion concentrations between the two sub-basins in conjunction with increasing ion concentrations with well depth. The equivalence method was used to determine groups of water types and plotting these geographically provides an indication of hydrochemical facies relative to geographical location and lithology type. There is a clear hydrochemical distinction between wells located in moraine deposits, wells located within or near active river beds, and wells located within or near bedrock highs.

Water-source rock interaction has also been reviewed to determine the influence of the source rock on groundwater chemistry. The bedrock is greywacke from the Torlesse Terrane and becomes metamorphosed towards the west. It is possible that the weathering of schist in the Ben Ohau Range on the west side of the basin is contributing to the higher calcium levels present within the Twizel sub-basin. The predominance of Ca-HCO_3 in the Tekapo sub-basin is thought to be from the weathering of feldspars within the greywacke sandstone.

CHAPTER 5

RECHARGE SOURCES AND GROUNDWATER AGE

5.1 INTRODUCTION

Sampling for recharge sources and groundwater ages was undertaken during October 2007 at the same time as water chemistry samples were collected. Oxygen-18 was analysed in attempt to define wells that are recharged either by rainfall or from rivers and samples were taken from 20 of the water sampling sites. Nine groundwater age samples were collected and analysed for chlorofluorocarbons and sulphur hexafluoride. Of the nine samples five were also analysed for tritium concentrations.

The main objective for analysing groundwater for age and recharge source was to provide the first set of data for the Mackenzie Basin, that defines how old the groundwater may be within the area and how quickly the groundwater system is recharging.

Defining the recharge source for the groundwater system can assist in determining the rate at which aquifers may be recharging. Several methods can be used to determine recharge sources including comparing similar water chemistry and oxygen-18 levels.

It has also been suggested that using chloride and nitrate-nitrogen concentrations can be used to determine rainfall recharge sites (Vincent, 2005). When determining recharge sources, other factors should be taken into consideration including aquifer material, residence times of water within the aquifer system, and possible contamination from anthropogenic sources. The chemistry of the subsurface has been taken into consideration when determining the recharge source as it is variable throughout the Mackenzie Basin.

5.2 RECHARGE SOURCE SAMPLING

To determine the recharge source for the groundwater in the Mackenzie Basin, oxygen-18 results have been combined with water chemistry analyses (see Chapter Four). The water chemistry data has been reviewed using the equivalance method (Rosen, 2001) and provides distinct hydrochemical facies for groundwater within varying geological conditions. The results from these methods are interpreted in section 5.3.

5.2.1 Oxygen-18 Results

For this study, 20 water samples were collected for analyses of the stable isotope $\delta^{18}O$ by Geological and Nuclear Sciences. The samples were taken from the three major lakes and 18 wells. Figure 5.1 illustrates the distribution of $\delta^{18}O$ values throughout the Mackenzie Basin. Prior to this study analysis using stable isotope tracers such as $\delta^{18}O$ has not been undertaken in the region. A discussion regarding the theory and occurrence of oxygen-18 and possible factors effecting oxygen-18 values are contained in Appendix 5A.

The $\delta^{18}O$ values range from -9.56 to -12.48. The lowest values are found in the three lakes and well H38/0051. The lakes have a more distinctive isotopic signature due to evaporation from the lake surface (van der Raaij, 2008). This distinct signature of leakage of evaporated lake water, and therefore enrichment of $\delta^{18}O$, has been used elsewhere in New Zealand to determine recharge sources (Stewart & Taylor, 1981).

The more positive values are located in the northwest region and become more negative (depleted in heavy isotopes) moving towards the east side of the Mackenzie Basin. This trend is contradictory to the trend found on the Canterbury Plains where $\delta^{18}O$ values are more negative inland compared to those obtained on the east coast. The $\delta^{18}O$ value for rainfall close to the foothills on the Canterbuy Plains is around -8.5. $\delta^{18}O$ values can be used on the Canterbury Plains to define recharge source as there is a distinct variation between rainfall recharge and river recharge sites. This is due to major rivers being fed by high alpine catchments which have more negative $\delta^{18}O$ values. Therefore the use of $\delta^{18}O$ to distinguish between river and rainfall recharge within a high alpine basin is difficult.

It is possible that the $\delta^{18}O$ values within the Mackenzie Basin follow a westerly air flow trend where enriched rainfall is ‘raining out’ isotopes closer to the west, near the Main Divide and other ranges such as the Ben Ohau Range, and therefore rain in the east is more depleted in $\delta^{18}O$. This assumes that the rainfall infiltration in the east side of the basin is derived from north westerly flows.

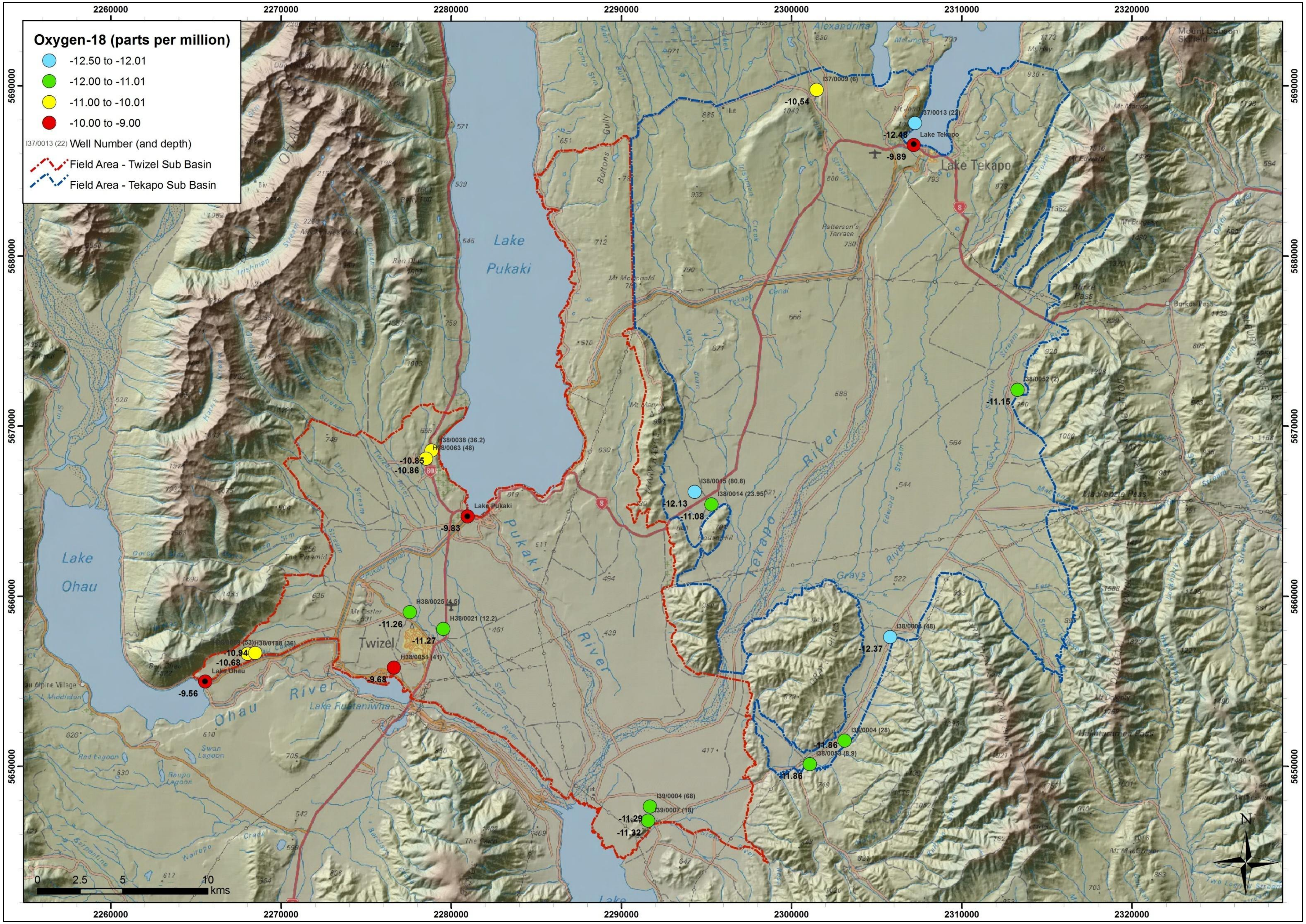


Figure 5.1: Distribution of oxygen-18 sample locations, and resulting oxygen-18 values following analysis by GNS. The depth of the well for each sample is also indicated.

5.2.2 Chemistry Analyses

The common sources of recharge are from rainfall infiltration through the subsurface and downwards leakage from surface water flows such as rivers and streams. Each of these recharge sources can provide their own distinct chemical signature. Rainfall tends to be enriched with regard to chloride. As rainwater moves through the soil and unsaturated zone it reacts with minerals and nutrients present, enriching the solution with ions such as calcium, magnesium, and chloride (Vincent, 2005). The enrichment of rainfall that has passed through the subsurface is demonstrated by data collected in lysimeters. Unfortunately there are no lysimeters within the study area or close by. The Hororata lysimeter data (located in the upper Canterbury Plains) can be used to illustrate the increase in chloride and nitrate nitrogen concentrations as rainfall passes through the soil (Table 5.1). It can be seen that rainfall at this site is enriched with respect to chloride, on average, from 3.72 mg/L to 16.4 mg/L as it passes through 80 cm of soil. Using chloride concentrations to distinguish recharge sources is useful in the Canterbury Plains as there is little exchange of chloride within the aquifers (Vincent, 2005). It was also noted that chloride concentrations tend to decrease to the west, away from the coast, on the Canterbury Plains, where the minimum chloride values are between 10 to 20 mg/L for rainfall recharged groundwater (Vincent, 2005). On the Canterbury Plains where rainfall has a greater influence than river recharge δ^{18}O values will become more positive in conjunction with increasing chloride and nitrate nitrogen levels (Taylor *et al.*, 1989). Within the study area chloride concentrations are significantly lower, (average concentration 1.3 mg/L) and levels decrease towards the west.

Table 5.1: Hororata lysimeter site data **-** δ^{18}O, chloride, nitrate nitrogen data for both rainfall and soil drainage at 80 cm depth (Stewart, 2005).

Year	Rainfall				Soil Drainage				Sample Period
	Depth (mm)	^{18}O (‰)	Cl (mg/L)	NO_3-N (mg/L)	Depth (mm)	^{18}O (‰)	Cl (mg/L)	NO_3-N (mg/L)	
1999	496	-8.54	-	-	216	-9.03	-	-	6
2000	883	-8.84	2.88	<0.2	408	-9.69	8.06	0.05	12
2001	728	-7.02	2.4	<0.3	270	-6.92	20.61	0.68	12
2002	533	-8.58	3.3	<0.3	47	-8.28	4.74	<0.3	12
2003	741	-7.84	2.27	<0.3	230	-7.25	28.04	2.11	12
2004	577	-8.67	8.89	0	108	-8.05	17.68	1.76	12
Mean	**692**	**8.17**	**3.72**	**<0.3**	**213**	**8.23**	**16.4**	**0.83**	

Stiff plots have been used to display the major ion concentration of the water samples, which were discussed in Chapter Four. The Stiff plots have been coloured, first in relation to the chemical facies (equivalence method), and secondly to the oxygen-18 value for each sample to try and determine the recharge source.

5.3 RECHARGE SOURCE INTERPRETATION

Table 5.2 summarises the data used to determine the possible recharge source for each sample. Samples have been grouped based on chemical facies determined by the equivalence method (see Chapter Four), TDS levels, oxygen-18 values, and lithology of the well location. The method of determining recharge source based on chloride and nitrate nitrogen levels have been used successfully in the Canterbury Plains. However, the concentrations of nitrate nitrogen are very low within the Mackenzie Basin and therefore have not been used. Chloride levels are also extremely low in comparison to the Canterbury Plains; therefore these values have only been included for comparison with the Canterbury Plains area. However, there is a trend of increasing ion concentration with increasing chloride levels which would suggest that the Tekapo sub-basin is recharged by rainfall as there is less river water to dilute enriched rainfall within the area. This trend is seen in wells I38/0003, I38/0004, I38/0053, I38/0014, I38/0015, I39/0004, I39/0007, and I37/0013.

The groups of recharge source include rainfall recharge, river recharge, lake leakage recharge, and mixing of different recharge sources. The samples taken from the three lakes have been included for comparison. The Stiff plots with colours corresponding to the hydrochemical facies are shown in Figure 5.2. The same Stiff plots have also been used to illustrate the geographical distribution of the different hydrochemical facies (Figure 5.3).

5.3.1 Lake Recharge

All three lakes have similar water chemistries and $\delta^{18}O$ values (-9.56 to -9.89). There is one well that shows a similar chemistry and $\delta^{18}O$ value (H38/0051). It is likely that this well is being recharged from leakage from Lake Ruataniwha. Lake Ruataniwha derives its water from Lakes Ohau and Pukaki via the canal system.

5.3.2 River Recharge

The Mackenzie Basin acts as a recharge source for lower altitude regions such as the Lower Waitaki area, therefore distinguishing between river and rainfall recharge sources can be difficult to define. Many of the wells that are thought to have river recharge based on Table 5.2 have been suggested as having rainfall recharge by van der Raaij (2008). This is based on more negative $\delta^{18}O$ values, low recharge air temperatures and high excess air (calculated from the ratio of dissolved nitrogen and argon concentrations) (see Appendix 5B**)**. The age tracer and recharge source report suggests that H38/0059, H38/0063, I38/0052, I38/0014, I38/0015, and I37/0013 have rainfall derived recharge sources. It is possible that the difference in interpretation of the results is from these wells being so close to the Ben Ohau Range, the Mary Range, the Rollesby Range, or the Grampian Mountains, where both rain falls and the surface water flows originate. Therefore, as rainfall is the source of the surface water flows this water virtually has no time to become differentiated chemically.

Wells H38/0004, H38/0021, H38/0025, H38/0032, H38/0035 are all located within or close to the active river beds within the Twizel sub-basin. All of these wells have a very similar chemistry and have the lowest TDS values and ion concentrations measured within the Mackenzie Basin. Based on their location within the riverbeds these wells have been identified as having a river recharge source. Therefore their chemical signature can be used to identify other wells that are also likely to have a river recharge source.

Within the Twizel sub-basin wells H38/0038, H38/0057, H38/0063, and H38/0188 have been classified as having a river recharge source. Samples from these wells have moderate TDS concentrations and similar δ^{18}O values to the wells located within the active riverbeds in the Twizel sub-basin (for example H38/0025). It is likely that their chemistry is different to the wells in the riverbeds due to the variable aquifer lithology at these locations; most of the wells are located within moraine material (till). Additional support for the river recharge classification is their proximity to the foothills of the Ben Ohau Range where many of the surface water flows originate.

Well I37/0009, in the Tekapo sub-basin, has similar oxygen-18 values to the preceding wells; however the chemistry of the sample from this well is quite different. The well has been classified as river recharge due to its location and shallow depth within the active river bed of Fork Stream. In comparison, I38/0054 is likely to be recharged by the Mary Burn, but this stream is further from the head of its catchment and has lower river flow rates. It is also possible that I38/0054 is being recharged by both rainfall and river sources creating a mixture of recharge sources.

5.3.3 Rainfall Recharge

Four of the wells sampled (I38/0003, I38/0004, I38/0014, I38/0053) are most likely being recharged by rainfall. These wells are located within, or very near, alluvial fan deposits. The rainfall, falling near the top of the ranges surrounding these fans, slowly moves downwards through the alluvial material. This longer residence time allows for mineral and rock interaction, increasing total dissolved solids values and ion concentrations.

5.3.4 Mixing of Recharge Sources

Six of the wells sampled (I37/0013, I38/0015, I38/0052, I38/0054, I39/0004, I39/0007) indicate a mixture of recharge sources. Two of these wells were also analysed for recharge sources by van der Raaij (2008) who suggests river or lake recharge for I39/0004 and I39/0007 based on high recharge temperatures and low excess air. However, the report notes that the $\delta^{18}O$ values for both of these wells are significantly more negative than the values observed in the three lakes. Given the proximity to two major rivers and to Lake Benmore it is probably that these wells are encountering leakage from both the lake and the rivers.

Well I37/0013 is located in the bedrock of Mt John on the west side of Lake Tekapo. It is probable that the recharge for this well is rainfall slowly seeping through fractures within the bedrock. Given the proximity to Lake Tekapo it is possible that the well is also encountering some leakage from the lake; however this lake is perched and the well is artesian, indicating that the source of recharge is from the bedrock above the well.

Well I38/0015 is the deepest well sampled during 2007 (80.8 m), and is located close to alluvial fans on the Mary Range and is just south of surface water flows and springs contributing to the Mary Burn. It is suggested that this well is recharging slowly from rainfall via the alluvial fan, but is also possibly encountering subsurface flows through buried channels at depth from surface flows that are seen to the north of this site. The age dating report suggests that this well is recharged by rainfall based on low recharge temperature and high excess air (van der Raaij, 2008).

Well I38/0052 is located on the edge of an alluvial fan by the Rollesby Range and close to the active river bed of Bullocky Creek. It is possible that this well is encountering rainfall seepage through the alluvial fan as well as recharging from surface water flows in the creek nearby. It is suggested that this well is being recharged by rainfall, but that degassing may have occurred either prior to, or during sampling which may have affected the sample (van der Raaij, 2008).

Well I38/0054 is located in the active river bed of the Mary Burn and has similar water chemistry characteristics to that of I38/0052. This well was only sampled for chemical analysis during 2005 and therefore does not have any $\delta^{18}O$ analysis to make a comparison for recharge source interpretation.

Table 5.2: Summary of data for each sample to define recharge sources. The data is from the samples collected in October 2007 samples and from four samples collected in February 2005.

Stiff Plot Colour	Chemistry Type (Equivalence Method)	Well ID	Sub-basin	Chloride (mg/L)	TDS (mg/L)	Oxygen-18 (‰)	Lithology Type	Possible Recharge Source
Yellow	Ca-HCO_3	H38/0051	Twizel	0.37	77	-9.68	Mt John glacial outwash surface	Lake
		Lake Ohau	Twizel	0.34	51	-9.56	Lake	
		Lake Pukaki	Twizel	0.37	49	-9.83	Lake	
		Lake Tekapo	Tekapo	0.3	44	-9.89	Lake	
Orange	Ca-Na-K-HCO_3	I37/0009	Tekapo	0.28	148	-10.54	Active river bed (Fork Stream)	Undetermined (rainfall or river)
Red	Ca-Na-Mg-HCO_3	H38/0038	Twizel	0.85	88	-10.85	Tekapo moraine	River
		H38/0057	Twizel	0.3	66	-	Mt John glacial outwash surface (possibly in moraine at depth)	
		H38/0063	Twizel	0.76	74	-10.86	Mt John moraine	
		H38/0188	Twizel	<1	65	-10.68	Tekapo glacial outwash surface (possibly in moraine at depth)	
Dark Green	Ca-Na-HCO_3	H38/0059	Twizel	0.57	99	-10.94	Tekapo glacial outwash surface (possibly in moraine at depth)	Undetermined (rainfall or river)
Light Blue	Ca-Na-HCO_3	H38/0004	Twizel	0.4	34	-	Active river bed (Fraser Stream) (2005 sample)	River
		H38/0021	Twizel	0.46	30	-11.27	Active river bed (Twizel River)	
		H38/0025	Twizel	0.4	28	-11.26	Active river bed (Fraser Stream)	
		H38/0032	Twizel	0.7	34	-	Active river bed (Twizel River) (2005 sample)	
		H38/0035	Twizel	0.4	55	-	Tekapo glacial outwash surface (close to Twizel River) (2005 sample)	
Light Purple	Ca-Mg-Na-HCO_3	I38/0052	Tekapo	1.8	67	-11.15	Alluvial fan/Active river bed (Bullocky Creek)	Mixing (rainfall/river)
		I38/0054	Tekapo	1.8	111	-	Active river bed (Mary Burn) (2005 sample)	Possible Mixing (rainfall/river)
Dark Blue	Ca-Na-HCO_3	I39/0004	Twizel	1.4	113	-11.29	Tekapo glacial outwash/Close to bedrock high	Mixing (river/possible lake leakage)
		I39/0007	Twizel	1.6	94	-11.32	Tekapo glacial outwash/Close to bedrock high	Mixing (river/possible lake leakage)
Purple	Na-HCO_3-SO_4	I38/0004	Tekapo	4	260	-11.86	Close to bedrock high/Alluvial fan	Rainfall
Grey	Ca-Mg-Na-HCO_3	I38/0014	Tekapo	2.5	172	-11.08	Close to bedrock high/Balmoral glacial outwash surface/Alluvial fan	Rainfall
		I38/0053	Tekapo	3	174	-11.86	Close to bedrock high/Alluvial fan	
		I38/0003	Tekapo	4.2	127	-12.37	Close to bedrock high/Alluvial fan	
Light Green	Ca-Na-HCO_3	I38/0015	Tekapo	1.6	148	-12.13	Close to bedrock high/Balmoral glacial outwash surface	Mixing (rainfall/subsurface flows from streams in the north)
Black	Ca-HCO_3	I37/0013	Tekapo	1.3	196	-12.48	Close to bedrock high	Mixing (rainfall/possible lake leakage)

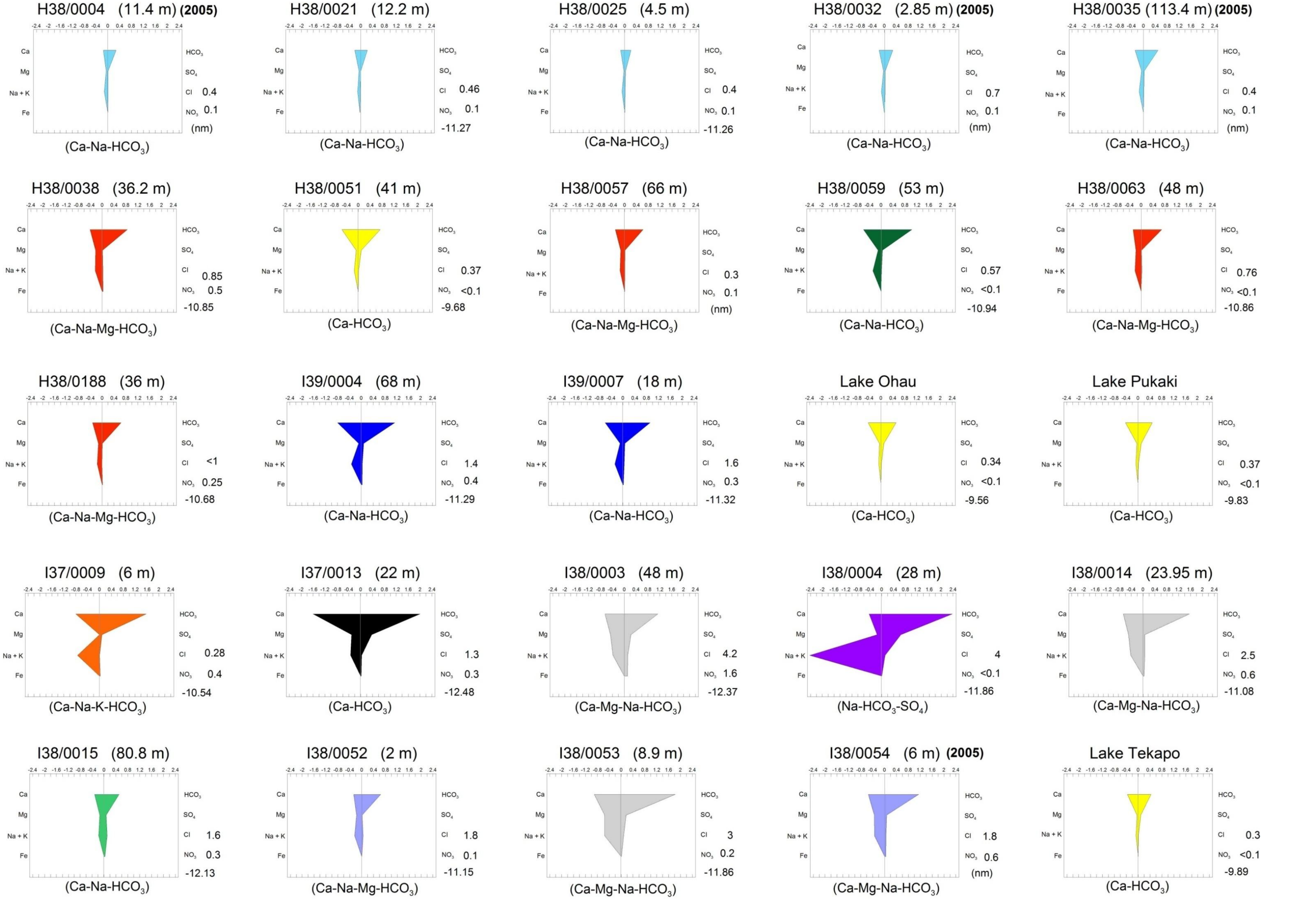


Figure 5.2: Stiff plots (in meq/L) – coloured by similar chemical facies (equivalence method) and oxygen-18 values. The chloride and nitrate nitrogen levels are shown to the right of the axis (in mg/L) and the oxygen-18 value (‰) is shown at the bottom right also. Four samples do not have an oxygen-18 value as they were sampled during 2005.

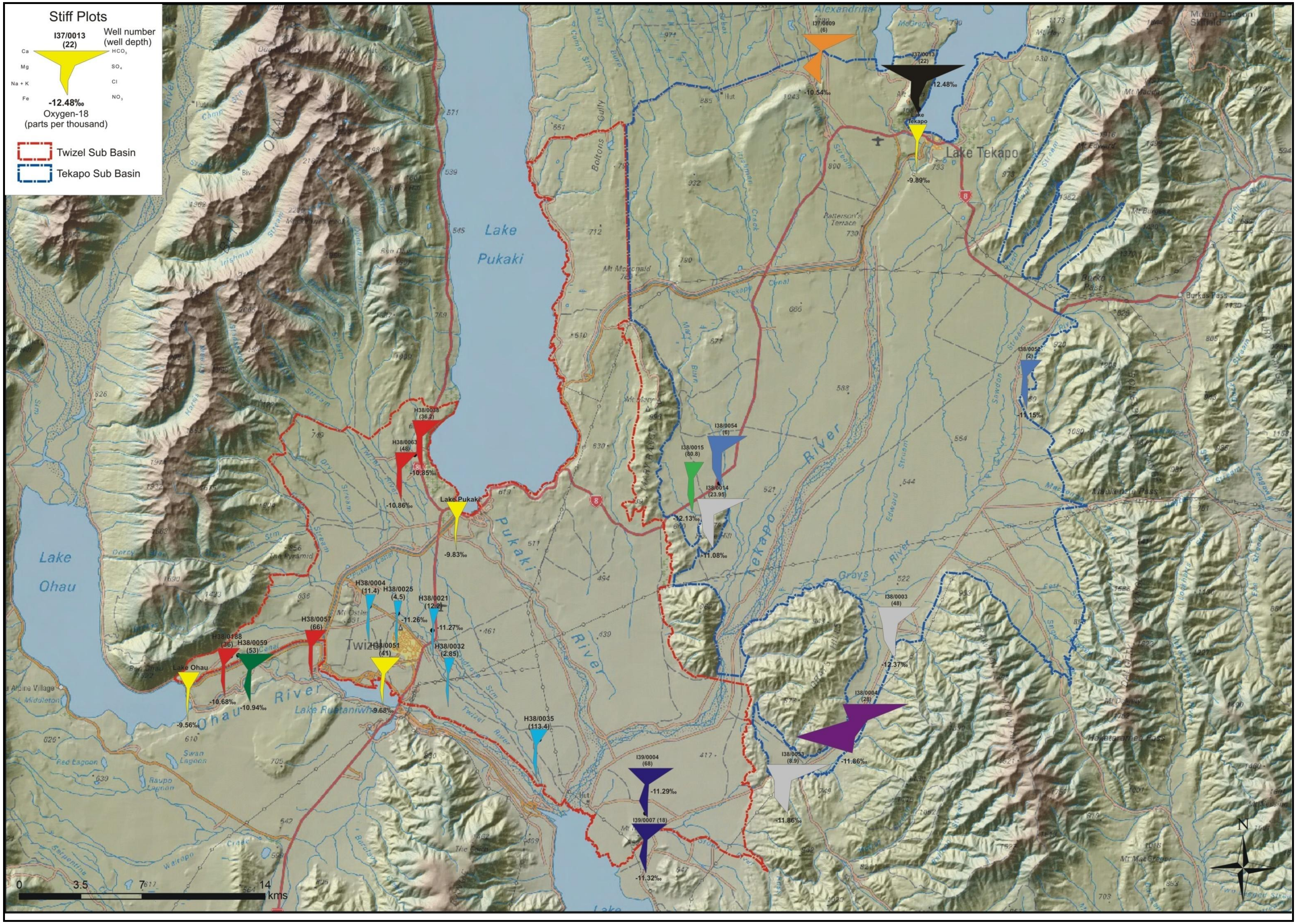


Figure 5.3: Geographical distribution of hydrochemical facies using stiff plots – coloured using the equivalence method and relative to oxygen-18 values.

5.4 GROUNDWATER AGE

In conjunction with understanding recharge sources, storage volumes and flow rates, determining the age (residence time) of groundwater can help in understanding groundwater resources for sustainable management purposes (Stewart & Morgenstern, 2001).

Groundwater age is closely related to the rate at which groundwater moves through the subsurface; flow velocity is the reciprocal of the age gradient which is the rate that age changes with distance along the flow path. The slower that groundwater moves through an aquifer, the longer the residence time resulting in older groundwater ages (Benthke & Johnson, 2008).

Groundwater ages can also be used to indicate mixing of aquifers, possible pathways of groundwater flow, flow rates, and the sustainable yield of the resource (Stewart & Morgenstern, 2001; Weissman *et al.*, 2002). Understanding groundwater age can also identify impacts of past and present land use practices on water quality (Daughney & Reeves, 2005).

It has also been suggested that groundwater ages can be estimated using hydrochemistry data. Many results from age dating tracers can be ambiguous or have a range of ages that may be possible due to the mixing of groundwater within the aquifer and the well; hydrochemistry may provide a way to overcome these issues (Daughney *et al.*, 2007).

Three types of age dating tracers have been used to determine groundwater age for this study: chlorofluorocarbons, sulphur hexafluoride, and tritium. A discussion on the groundwater age dating methods and problems is contained in Appendix 5C.

5.4.1 Age Dating Tracer Results

During October 2007, nine of the 20 wells sampled were analysed by Geological and Nuclear Sciences (GNS) to determine the groundwater age using age dating tracers. The nine samples were analysed for CFCs and SF_6. Of those nine samples, five were also sampled for tritium. All samples were collected using the guidelines provided by GNS (Rosen *et al.*, 1999). Groundwater age dating within the Upper Waitaki area has not been conducted prior to this study.

All of the results from GNS are given as an age range rather than a specific age, in part due to possible contamination and in part due to the percentage for the exponential piston flow model being an unknown for this type of area. Some of the suggested ages are also indicated as greater than a certain age, leaving the actual age open to interpretation (Table 5.3).

Table 5.3: Mean ages using tritium, CFC-11, CFC-12, and SF_6 in conjunction with the exponential flow model.

Well Number	Well Depth (m)	Screened Interval (m)	Exponential Flow Model %	Mean Age (based on Exponential Flow Model Indicated)				Recomm-ended Age (years)
				Tritium	CFC-11	CFC-12	SF_6	
H38/0051	41	39 - 41	50	nm	24	13	**C**	?
H38/0059	53	49 – 53	50	>95	>124*	89*	51	>95
H38/0063	48	37.5 – 47.5	50	>93	90*	93*	59	>93
I39/0004	69.6	61.6 – 69.6	50	80 – 82	83	80	40	80 – 82
I39/0007	18.5	nm	50	nm	42	35	11	11 – 42
I37/0013	22	19.8 – 22	30	27 – 29, 54	54	46	23	23 - 54
I38/0014	23.95	23 – 23.95	50	nm	66	54	>100	>100
I38/0015	80.8	74.8 – 80.8	50	92 – 115	94*	96*	45	92 – 115
I38/0052	2	nm	90	nm	25	16	**C**	?

***** denotes CFC concentrations that may be affected by degradation due to anoxic conditions within the aquifer
C denotes samples contaminated above that possible for water in equilibrium with modern CFC or SF_6 concentrations in air
nm denotes sample not measured for age tracer

The location of wells sampled for age dating traces are shown in Figure 5.5. The range of recommended ages is from 11 to 115 years for seven of the samples. No age is suggested for two of the samples which were contaminated for SF_6 analysis and were not analysed for tritium (H38/0051 and I38/0052). The suggested age from tritium analysis has been used for interpretation in the three samples that were contaminated for CFCs and SF_6 analysis (I38/0015, H38/0063, and H38/0059). There is no correlation with groundwater age and sub-basin area. The range of groundwater ages is distributed throughout the Mackenzie Basin (

Figure 5.6). However, the sample size is small given the size of the study area, and the sample size is reduced as two of the samples were contaminated and could not be used for age determination. There is a distinct grouping of ages, however, one group ranges from 11 to 23 years, and another group ranges from 80 to 115 years (

Figure 5.6).

As a range of ages is given for each sample, the lower age has been used for comparison with other determinands. Graphs for comparative purposes can be found in Appendix 5D. There is a moderate correlation of groundwater age with screen depth, generally the age of the water increases with the depth of the well (Figure 5.4). Age has been compared with total dissolved solids; there is no correlation between the two within the Twizel sub-basin, and only a low correlation in the Tekapo sub-basin ($R^2 = 0.13$). Comparisons have also been made with sodium, sulphate, and dissolved oxygen with groundwater age results, similar to the study of Zuber *et al.* (2005). The Tekapo sub-basin shows a strong correlation of increasing sodium concentration with age, but low correlations of reducing dissolved oxygen and sulphate levels with increasing age. The Twizel sub-basin has stronger correlations with dissolved oxygen and sulphate, levels of both decreases with increasing groundwater age. The Twizel sub-basin also has a correlation, but not as strong as the Tekapo sub-basin, of increasing sodium levels with increasing age.

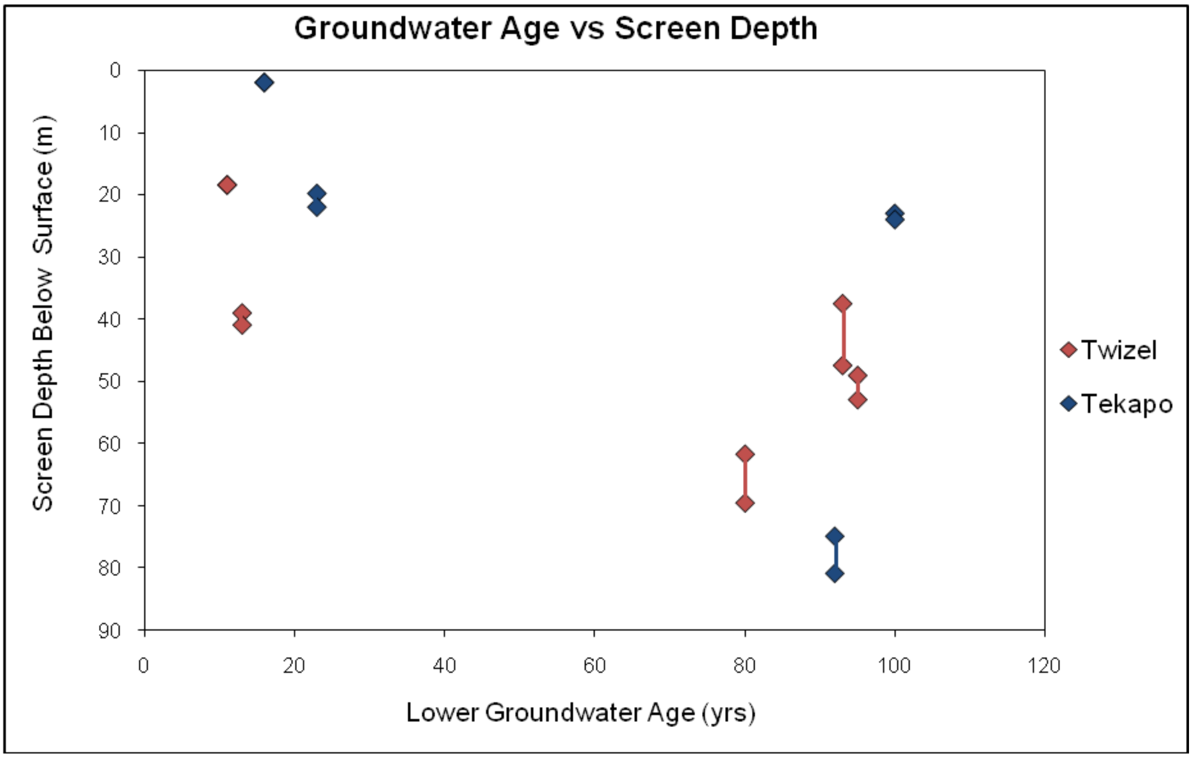


Figure 5.4: Comparison of screen depth within the well and groundwater age. As age ranges have been suggested for most samples the lower age has been used for plotting purposes. The two samples with no recommended age have been plotted using the suggested age from the CFC-12 analysis. The lines indicate the screened interval within the well.

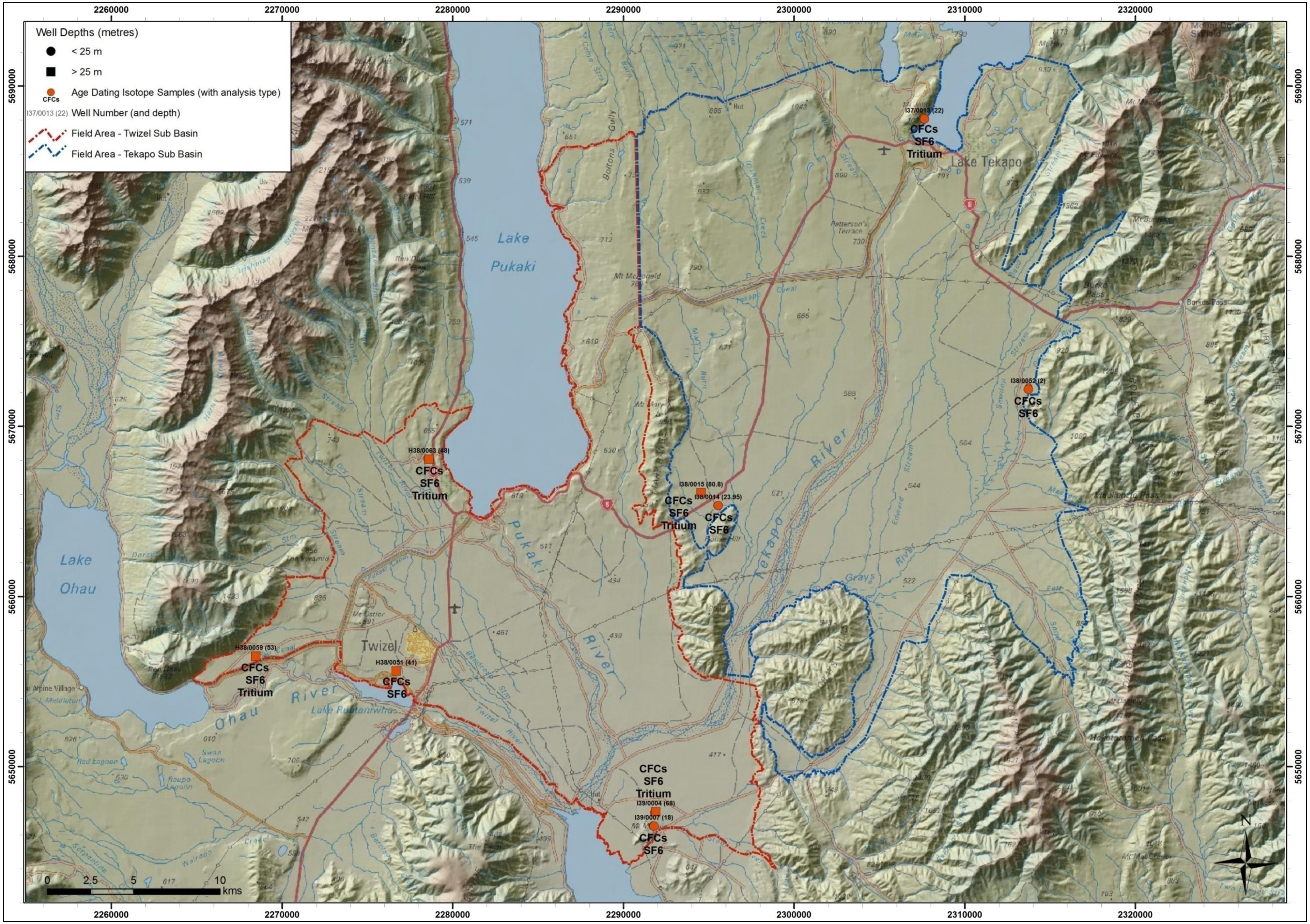


Figure 5.5: Location of wells sampled for CFCs, SF_6, and tritium.

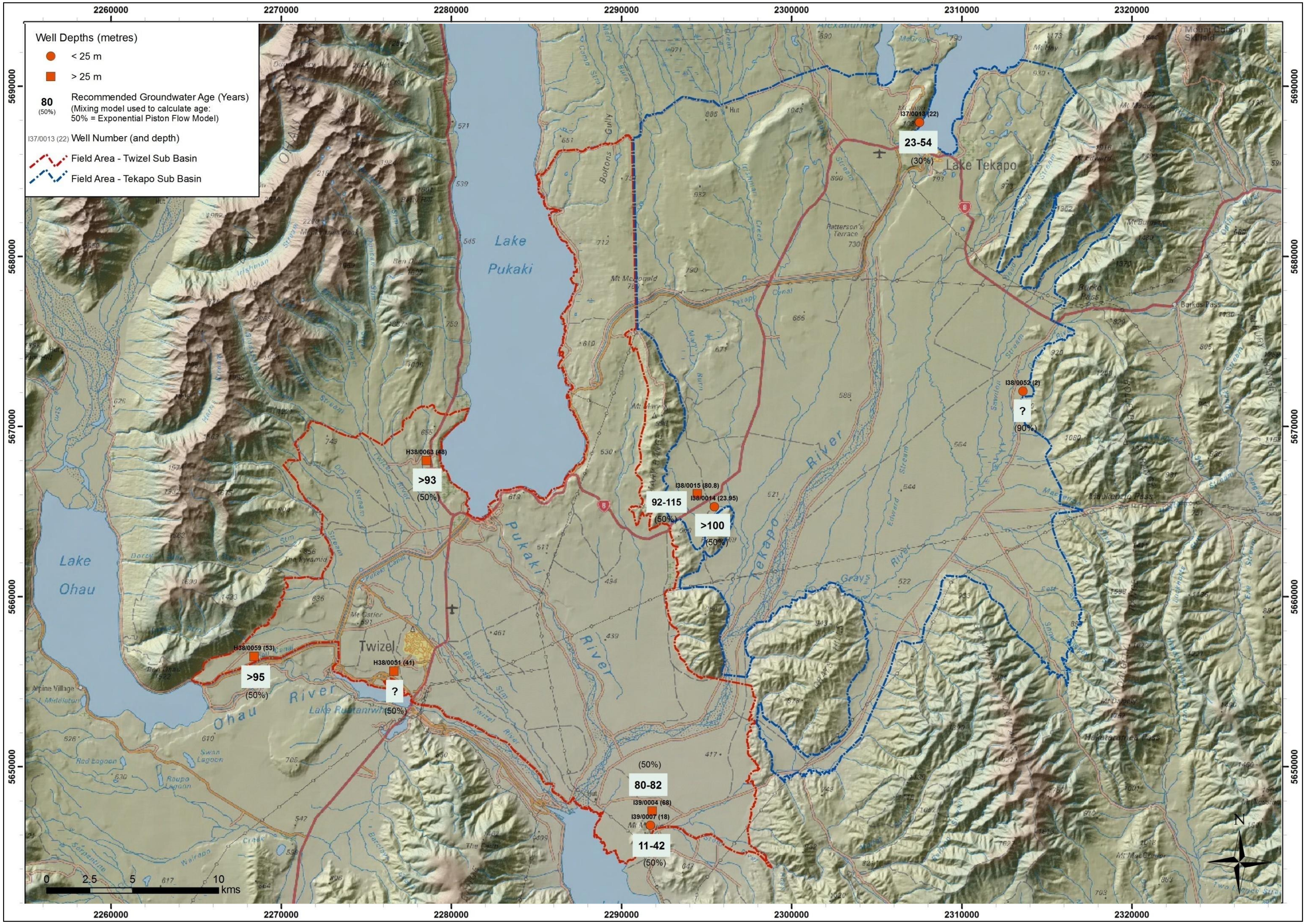


Figure 5.6: Geographical distribution of groundwater age throughout the Basin. The ages indicated are the recommended ages from van der Raaij (2008).

5.4.2 Groundwater Age Interpretation

5.4.2.1 Older Groundwater

There are five samples with relatively old groundwater (H38/0059, H38/0063, I38/0014, I38/0015, I39/0004), however it has been noted by van der Raaij (2008) that there is insufficient data to determine the most appropriate exponential mixing amount to use in the piston flow model. A representative 50% value was chosen on the basis of well depth and narrow screen interval. Values of 50% have been used within the Canterbury Plains and are thought to be representative for alluvial aquifers (van der Raaij, 2008). CFC degradation may have occurred in H38/0059, H38/0063, and H38/0015 which all have levels of dissolved methane, detectable levels of iron, and relatively low dissolved oxygen concentrations. Degradation of CFCs can result in ages that are too old. For these three samples, all three types of age tracers were used, therefore giving more reliability to the suggested ages which are primarily based on the results of the tritium analysis. All of these wells are relatively deep (>25 m), with the exception of I38/0014 (23.95 m deep).

I38/0014 and I38/0015 (80.8 m deep) are in close proximity to each other (~1,200 m). The analyses for these wells have been dissimilar in all respects with the exception of the recommended age (92-115 and >100). It is thought that I38/0015 is encountering subsurface flows of water from surface water flows located to the north of this site, and that the well has encountered a buried channel at depth. I38/0014 is thought to be a mixture of subsurface flows from streams and infiltration of rainfall through the alluvial fan close to the well location (based on hydrochemical facies). Both of these wells are in an area mapped as the Balmoral Outwash Gravels, which is suggested to have a low permeability. However, from the bore log description I38/0014 appears to be semi-confined in nature, but due to the braided buried channels within the subsurface it is possible that the aquifer may only be very locally confined near the well location and actually be unconfined further away. It is also possible that due to the direction of groundwater flow towards the southwest, and the proximity to the bedrock high of the Mary Range, that this well is picking up older water rising from a greater depth as the bedrock topography at depth begins to shallow towards the southwest of this area. Both of these wells were drilled by the same landowner, and it was found that the yield for I38/0015 was too low to be of any use; in contrast the yield from I38/0014 was high enough to supply both domestic and stock water for the station. This difference in yield could represent the confining nature of the aquifer or that the recharge source is from multiple sources and not just from the low permeability Balmoral Outwash Gravels.

Well H38/0063 is located within the Mt John moraine, which is composed of a high silt and clay content. It is suggested that the older age of this groundwater is likely to be due to the aquifer lithology and therefore probably low recharge rates.

Well H38/0059 is located within the Tekapo Outwash Gravels (mapped at the surface). This well is less than 1 km from the Ben Ohau Range and it is likely the thickness of sediments is not extensive. The bore log indicates that the well screen is within a unit containing white silt, blue sand and small blue gravels. The lithology description is quite different to surrounding well logs and is possibly picking up an older glacial/interglacial unit at depth. The aquifer is also overlain locally by a blue silty clay plug which would decrease downwards infiltration of rainfall from above. The high fines content in this well is likely to be similar to that of H38/0063, therefore providing a similar groundwater age. Both of these wells also have similar hydrochemical facies and $\delta^{18}O$ values (-10.94 and -10.86). However, it must be noted that both of these wells had CFC degradation.

The suggested recharge source for I39/0004 is likely to be a mixture of lake leakage and river recharge. This well is approximately 750 m north of a bedrock high (Mt Maggie) and could possibly be encountering an upwelling of older groundwater as the groundwater moves south towards Lake Benmore and encounters the bedrock mound. This may cause the groundwater to move towards the surface**.**

5.4.2.2 Younger Groundwater

Well I37/0013 is an artesian well located on the east side of the bedrock high of Mt John, located on the west shore of Lake Tekapo. It is thought, given the artesian nature of the well that the recharge source is via rainfall seepage through bedrock fractures. Along the same altitude of Mt John flowing springs are evident, supporting this idea. However, the bore log indicates that the well screen is located within grey gravels and white silt, overlain by 11 m of yellow clay. The hydrochemistry for this well is similar to that of Lake Tekapo, but the $\delta^{18}O$ value is significantly more negative (-12.48 compared to -9.89 of Lake Tekapo) making it uncertain as to whether this well is encountering leakage from the lake. The CFC and SF_6 ages for I37/0013 are quite different due to gas tracer concentrations, but this well has also been tested for tritium making the recommended age more reliable. The exponential piston flow model used for this well was 30% due to its artesian nature (van der Raaij, 2008). It has been suggested that the SF_6 model age should be regarded as a minimum age (23 years) for this well due to the diffusive processes in the unsaturated zone (van der Raaij, 2008).

Well I39/0007 is a shallower well located approximately 1,100 metres south of I39/0004. Again, the gas tracer concentrations in this sample have created greatly differing model ages. A 50% exponential piston flow model has been used resulting in a mean age of at least 11 years. The hydrochemistry of this sample is the same as I39/0004 and is therefore regarded as being recharged by lake leakage or river recharge. I39/0007 is closer to the bedrock high of Mt Maggie than I39/0004, so it is therefore possible that this well is also encountering recharge from rainfall seepage through bedrock fractures.

Both H38/0051 and I38/0052 samples were contaminated, either during sampling or due to the type of well, for SF_6 age tracer analysis and neither sample was tested for tritium. Therefore these samples were only able to be analysed for CFCs. It is recommended that both of these be re-sampled for tritium to confirm the groundwater age.

I38/0052 has undergone significant degassing which has increased the uncertainty of the gas tracer analysis results. As this well is only 2 m deep an exponential piston flow model using 90% was used. The CFC concentrations suggest older water, but CFC degradation or physical processes within the unsaturated zone (adsorption or diffusion) may have occurred (van der Raaij, 2008). I38/0052 is located on the edge of an alluvial fan and close to an active river bed. The area surrounding the well is very swampy indicating that groundwater levels within the area are very shallow. The mixing of river recharge and water flowing through the alluvial fan is likely to result in fairly young water as suggested by the CFC results; however the reliability of using only one age dating tracer makes the age suggested by this method very uncertain.

H38/0051 is located on the east shore of Lake Ruataniwha near Twizel. The hydrochemistry and $\delta^{18}O$ for this well are nearly identical to the water sample taken from Lake Ohau to the west of this site. It has been suggested in Chapter Four that this well is encountering lake leakage at depth. As this well is fairly deep (41 m) with a narrow well screen interval an exponential piston flow model of 50% was used (van der Raaij, 2008). As the sample was contaminated for SF_6 analysis no recommended age has been provided, but the CFC concentrations suggest an age of 13 to 24 years old, and given the likely recharge source it is possible that this age is representative of the groundwater.

5.5 CHAPTER SUMMARY

In comparison to the Canterbury Plains, the oxygen-18 values are more negative throughout the Mackenzie Basin ranging from -9.56 to -12.48. The use of oxygen-18 values to delineate between rainfall and river recharge sources works well in the Canterbury Plains due to more negative oxygen-18 values found in rivers with high alpine catchments. However, as the Mackenzie Basin is an alpine basin this technique does not appear to be as useful to define recharge sources. Within the basin rainfall is also derived mainly from the northwest compared to the south easterly source of the Canterbury Plains. The three lakes have a definite oxygen-18 signature and this is apparent in the well that encounters lake leakage at depth. Oxygen-18 samples were not collected from rivers or streams flowing from the hills surrounding the basin, which makes confirming river recharge sources difficult.

Other techniques that have been used on the Canterbury Plains have also been used within this study. Chloride and nitrate nitrogen levels have been reviewed to determine whether they can be used for recharge source delineation. In the Canterbury Plains, chloride and nitrate nitrogen levels will generally increase with rainfall derived recharge sources. However, nitrate nitrogen levels within the basin are very low and chloride levels are also low. Instead the chemical facies determined from the equivalence method used in Chapter Four, in conjunction with TDS concentrations and oxygen-18 values, have been used to suggest recharge sources. From this it is suggested that the Tekapo sub-basin is predominantly a rainfall recharged area and the Twizel sub-basin is recharged by mainly by surface water flows.

Groundwater ages within the Mackenzie Basin are young (<1000 years), but are generally not relatively modern in age. The ages range from 11 to 115 years throughout the area. The results for the age dating tracer concentration analyses have been provided as a range of ages for each sample, and therefore the exact ages cannot be determined at this stage. It is likely that sampling of more wells, or the same wells in the future, will enhance the age dating procedure and provide more information that can be used in the analysis technique (i.e. the percentage of mixing to use for the exponential piston flow models). It has been suggested that other methods could be used in conjunction with age dating tracers to better define the groundwater age. These methods include hydrochemistry and predictive modelling, as well as transport modelling to define the amount of groundwater mixing that may be occurring within the subsurface. The dating of groundwater can be ambiguous due to the complex nature of groundwater with different ages mixing within aquifer systems.

CHAPTER 6

SURFACE HYDROLOGY AND SPRINGS

6.1 INTRODUCTION

Springs and surface water play an important role for farming within the Mackenzie Basin. By identifying and quantifying springs and surface water, interactions with the groundwater system can also be identified. In this study springs have been located for further investigation. River gaugings have only recently been restarted in the area; therefore historical data has been reviewed in conjunction with gaugings undertaken within this study.

To further understand the interaction of groundwater and surface water flows, springs were mapped throughout the Mackenzie Basin. Prior to this study three springs were noted in the Springs Database held by Environment Canterbury. In December 2007, 53 permanently flowing springs were located based on information from local farmers. It was decided to locate permanent springs at this stage due to the large number of springs over a wide area. The presence of intermittent springs was noted based on the comments from farmers. Other permanent springs have been located based on discussions with farmers, but have not been observed in person. Not all areas were reviewed due to access restrictions. Each spring was located and noted using a handheld GPS and photographed. The classification and descriptions are based on Environment Canterbury's Springs Database Manual (Earl, 1998). The classification sheet used to determine the spring type and morphology is contained in Appendix 6A. Examples of each type of spring are shown in Figure 6.1.

There are two types of springs that are predominant within the Mackenzie Basin. A summary of the types of springs located during mapping and those on Environment Canterbury's Springs Database are listed in Table 6.1, and a full list of the springs located is contained in Appendix 6B. The locations of the springs are shown in Figure 6.2. The photographs of all springs located are in Appendix 6C.

Table 6.1: Summary of spring types of springs located during this study.

Spring Type	Discharge Variability	Number Located
Depression	Permanent	34
Fracture-Joint	Permanent	12
Contact	Permanent	7

6.2 SPRING ANALYSIS

6.2.1 Depression Springs

Many of the springs are depression springs formed where the water table has intersected the ground surface due to a change in topography. Fetter (2001) notes that changes in topography create corresponding undulations of the water table, and a spring is formed at the local discharge point of the water table. The best examples of this type of spring within the Mackenzie Basin are seen in the Twizel River, Fraser Stream, and Bendrose Stream areas within the Twizel sub-basin (see Figure 6.1 – B). To the north of Twizel, close to the Ben Ohau Range, surface water flows are numerous. As the flow within the streams moves towards the south there is interaction with the groundwater system. Close to the Twizel township the water flows re-emerge on the surface as depression springs, often with a point source morphology. It is likely that the exchange between groundwater and surface water is occurring due to changing lithologies at depth and water is encountering clay and silt lenses which force the groundwater to the surface at discrete locations**.** These springs act as recharge sources for surface water flows in the area of the active river bed of the Fraser and Bendrose Streams and the Twizel River. The observed flow from these depression springs is quite high and is used for stock water. Depression springs were also located in the Tekapo sub-basin close to the Tekapo River and the Mary Burn confluence. Springs emerge from the base of the terrace on the north side of the Tekapo River. It is likely that these springs are a discharge point of the water table flowing from the north beneath the Tekapo Outwash Gravels.

6.2.2 Fracture Springs

The second predominant type of springs are the fracture/joint springs located in most bedrock areas such as the Mary Range, Grays Hills, House Hill, the Rollesby Range, and the Grampian Mountains. The fractures within the very low permeability greywacke bedrock provide pathways for rainfall to infiltrate and move through the bedrock areas. Where these fractures intersect the ground surface, springs are found (Fetter, 2001). Many of the fracture type springs are used for stock and domestic water for many farms within the Tekapo sub-basin. It has been stated by farmers within the area that many of these springs have flowed for more than 50 years and are therefore seen as a reliable source of water. However, it has also been noted that in some areas these flows have decreased over the last five years, and in some cases the springs have ceased to flow. The springs that have been located during this study are all permanently flowing springs; however farmers have also observed ‘hundreds’ of intermittently flowing springs in bedrock areas following periods of heavy rainfall. Many of the springs located and noted by farmers are found to be at a common elevation within the bedrock areas. This suggests that rainfall infiltrating the surface comes to a point where the fractures are either not present or are too tight for groundwater to move through. This creates the effect of a mounding of groundwater within the bedrock forcing the water to the surface at a common elevation.

6.2.3 Contact Springs

To a lesser extent, contact springs are present within the Twizel sub-basin. On the north side of the Ohau River a line of springs can be seen emerging from the terrace. Given their location within the terrace, it is suggested that these springs result from alluvial gravels overlying the less permeable Mt John Outwash Gravels. This suggests that the shallow groundwater flowing through the Twizel area is ‘perched’ above the lower permeability glacial gravels, and moves through the system rapidly so that the water table has little time to infiltrate downwards. These contact springs were observed to have a horizon morphology. The elevations of the point at which these springs emerge are higher than the Ohau River, and are therefore a recharge source for the river.

There are also two major fault systems present within the Mackenzie Basin. Both the Ostler and Irishman Creek Faults represent a barrier to groundwater flow by bringing the less permeable Glentanner Formation to the surface. This lithological barrier forces groundwater flows to the surface forming springs. Springs have been observed at the base of the fault scarps of both of these faults.

A. Depression spring – seepage morphology

B. Depression spring – point source morphology

C. Fracture spring – seepage morphology

D. Contact spring – horizon morphology

Figure 6.1: Examples of spring types located during mapping.

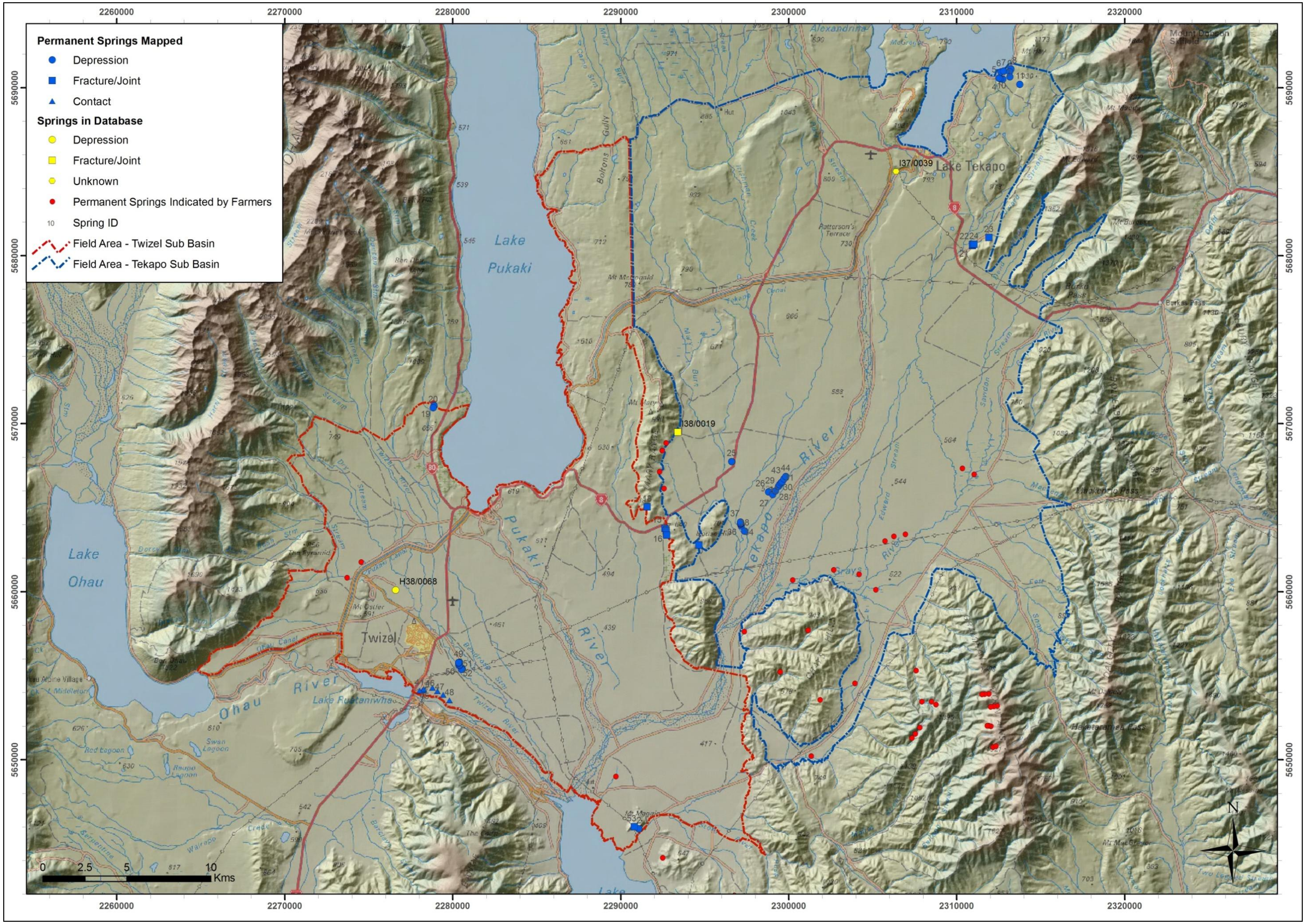


Figure 6.2: Location of springs mapped during 2007 and spring indicated by farmers on topographical maps.

6.3 SURFACE HYDROLOGY

There are a large number of streams and rivers within the study area which are predominantly fed from streams to the north and from the ranges surrounding the Mackenzie Basin. The main surface water flow paths are the Tekapo, Pukaki, and Ohau Rivers. Secondary flow paths are defined by the Mary Burn, Irishman Creek, Fork Stream, Grays River, Twizel River, Fraser Stream, and their many contributing tributaries. The three major rivers have been altered, however, as the inflows from the three glacial lakes has been diverted through the hydroelectric power canal system. Within the Mackenzie Basin surface water plays an important role for irrigation, stock water, and power generation purposes. There are a greater number of surface water takes compared to groundwater takes within the area. Many of the surface water streams are diverted through holding ponds for farming purposes.

6.3.1 Gauging Methodology

Over the last 40 years a number of gaugings have been conducted at sites throughout the Mackenzie Basin, and Environment Canterbury holds a large number of records in their Surface Water Database. Historical data located within the study area is presented in Appendix 6D. In October 2007, 22 gauging sites were chosen by the Surface Water Section of Environment Canterbury for concurrent gaugings to be carried out on a monthly basis (Figure 6.3). The purpose of conducting flow gaugings for this study was to determine flow gains and losses that are occurring that can indicate the interaction between surface water and groundwater. The gauging sites, and sites used for the concurrent gaugings graphs, are shown in Figure 6.4. Each river or stream was gauged at multiple sites on the same day, and all gaugings were done over a three day period by Environment Canterbury staff from Timaru. Flows were measured using a small horizontal axis Ott propeller and a NIWA current meter. Gauging sites were chosen that were clear of vegetation and other obstacles that may affect flow readings. Multiple readings were taken across the stream or river channel at 0.6 m of the water depth.

Figure 6.3: Examples of river gaugings undertaken in Deadmans Creek and the Twizel River.

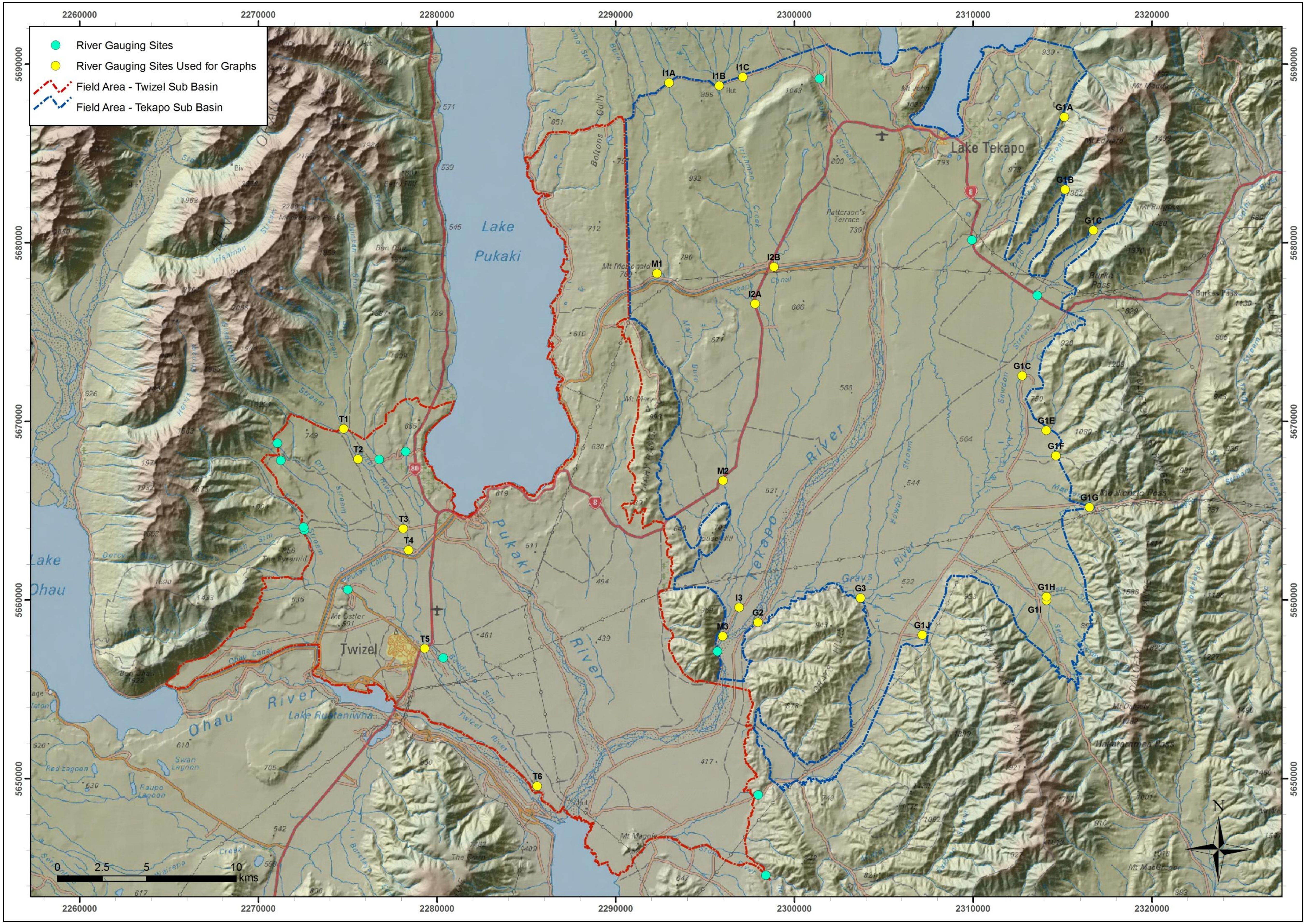


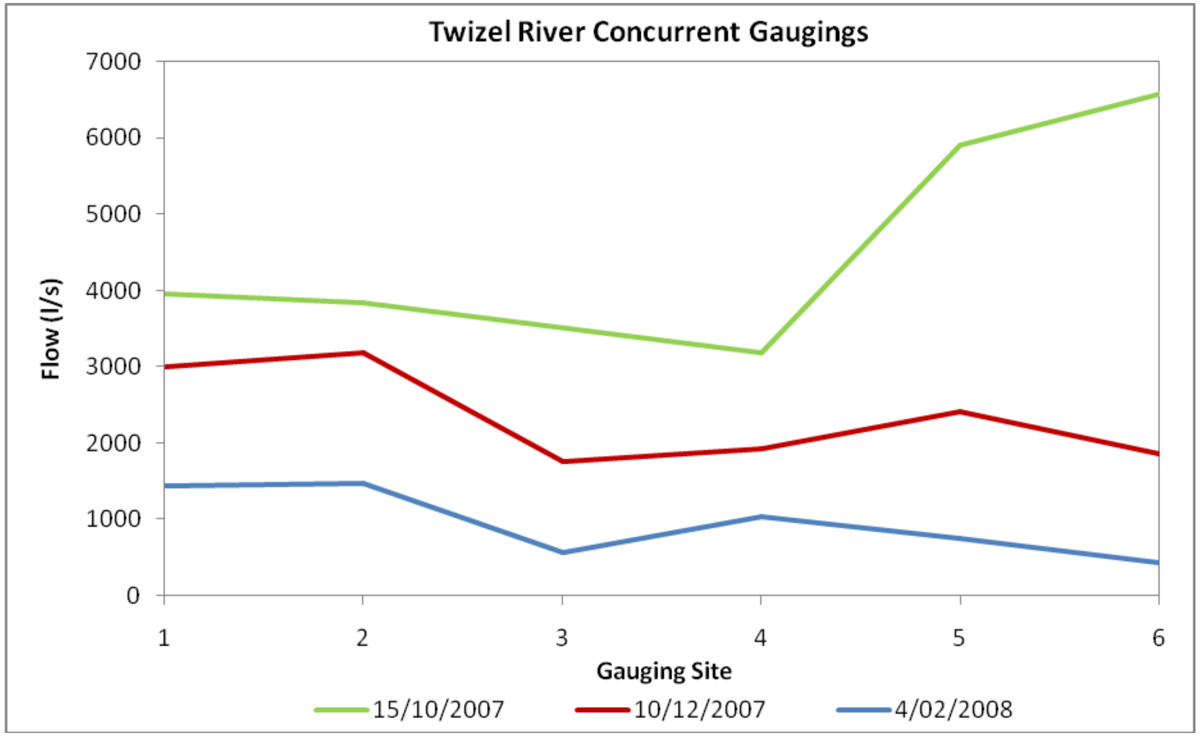
Figure 6.4: Location of river gauging sites. Sites discussed in the text are represented here as yellow symbols.

6.3.2 Results and Interpretation

The Tekapo and Twizel Rivers and the Mary Burn and the Irishman Creek have been chosen for the purposes of identifying gaining or losing reaches. A summary of results has been created for each of the four rivers, combined with a series of gaugings undertaken in 2004 for comparison. All graphs and results are contained in Appendix 6E. The flow rate was seen to decrease in the period October 2007 to February 2008 for all four rivers. Each river has losses and gains, indicating that surface water and groundwater do interact. However, there are other factors that have not been taken into consideration in this analysis, such as diversions for surface water takes and irrigation schemes. Also, the rivers and streams within the basin form a complex system with many small tributaries both joining and dividing from the major systems throughout the basin. The losses and gains for each of the four rivers are summarised below.

6.3.2.1 Twizel River

Six gauging sites indicate that the river both loses water to and gains water from the groundwater system (Figure 6.4). The data and graph illustrating the gaining and losing reaches of the Twizel River are shown in Figure 6.5. In comparison to the three rivers that have been gauged in the Tekapo sub-basin, the Twizel River provides a good data set (six concurrent gauging sites) with which to review the interaction of surface water and groundwater. North of the Pukaki canal between sites T2 and T3, there is a major loss to groundwater (between 80% and 160%). However, there is also a man-made surface water diversion in this area that could be reducing the water flow. In the area between the canal (T4) and State Highway 8 (SH8) (T5) the river gain water on average by approximately 35%. The water contribution is from numerous depression springs that emerge in this area. Between SH8 (T5) and the Tekapo River/Ohau River confluence (T6), surface water flows decrease again. This trend is mainly seen in periods of low flow (<1500 l/s). In periods of higher flows (>3000 l/s), especially during the spring period, this reach either gains water or the flow in the river is so high that there is insufficient time for water to be lost to the groundwater system. This area is very swampy and has a shallow groundwater table present at approximately 2 m below the surface. This indicates that the river is recharging the groundwater system during lower flow periods. Given that the Bendrose Stream also joins the Twizel River within this area it would be expected that the surface water flows would actually increase, therefore the contribution of surface water to the groundwater system must be significant



Site No.	Gauging Site	Measured Discharge (l/s)											
	Twizel River	15/11/2004			15/10/2007			10/12/2007			4/02/2008		
		Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)
T1	Twizel River #1	6248			3961			3004			1438		
T2	Twizel River #2	-	-	-	3835	-126	3	3180	+176	6	1476	+39	3
T3	Twizel River #3	-	-	-	-	-	-	1765	-1415	80	568	-908	160
T4	Twizel River #4	4221	-2027	48	3179	-656	21	1922	+157	8	1037	+468	45
T5	Twizel River #5	7409	+3188	43	5897	+2718	46	2418	+495	20	755	-282	37
T6	Twizel River #6	5943	-1466	25	6576	+679	10	1857	-561	30	435	-320	74

Figure 6.5: Flow gauging data and graph for the Twizel River for gaugings conducted in 2004, 2007, and 2008.

6.3.2.2 Mary Burn

Three gauging sites indicate that the stream mainly gains water along its reaches. The sharp increase in flows at sites M2 (SH8) and M3 (Tekapo River confluence) are likely to be from both springs and surface flows from the southeast combined with groundwater coming to the surface as it nears the bedrock high of House Hill/Grays Hills.

6.3.2.3 Irishman Creek

Three combined gauging sites indicate that in the months of December and February, when flows were very low, that the creek neither gains nor loses surface water. During October, when flows were higher, the creek loses a large amount of water between I2 (SH8) and I3 (above the Mary Burn confluence) to either the groundwater system or as the creek joins the Mary Burn to the west. It has been documented, by local observations and from historic gaugings, that site I2 (SH8) flows year round and that approximately 1 km south of this site the flow completely disappears below ground (Figure 6.6). It has been noted in other reports that even in periods of very high flow at I2 (SH8) the creek is still ephemeral south of this site (Gabites & Horrell, 2005). During the study period the creek was only observed to have any water in the creek bed at grid reference 2299705 5669446 (mid way between I2 and I3) once and this was following a period of extremely high rainfall in the head of the catchment. This suggests that a very large amount of water from the Irishman Creek is recharging the groundwater system in this area (Figure 6.7). In periods of high flows (>1500 l/s) the approximately 260% of the surface water flow is lost to the groundwater system. However, during low flow periods (<250 l/s) there is virtually no exchange between the surface water and groundwater systems (2% loss). The higher flows of the creek can be seen in the Irishman Creek Gorge in Figure 6.8.

6.3.2.4 Grays River

The method for determining gains and losses for this river is complex. The gauging sites in the ranges both north and east of the Grays River have been combined into one value to be able to determine any gains or losses further to the south. In December and February, when flow rates were lower, surface water gains water from groundwater north of gauging site G2 (Grays Hills). Surface water is then lost to groundwater between site G2 (Grays Hills) and G3 (Tekapo River confluence) (Figure 6.9). The opposite relationship is illustrated for periods of higher flows in October. The two opposing trends seem unusual and possibly need to be reviewed with regard to data analysis or flow gaugings taken during the month of October. Another factor is the relationship of the Grays River system to the Tekapo River to the west. It has been suggested that the Tekapo River shares a hydraulic link with groundwater and to the Grays River.

Figure 6.6: The point at which the Irishman Creek becomes ephemeral (view looking north east) (Photo: A Meredith, Ecan).

Figure 6.7: Closer to House Hill the Irishman Creek reappears and joins the Mary Burn (view looking south west) (Photo: A Meredith, Ecan).

Figure 6.8: The Irishman Creek where it has incised through the Irishman Creek Fault (view looking north) (Photo: A Meredith, Ecan).

Figure 6.9: The confluence of the Grays River with the Tekapo River (view looking north east) (Photo: A Meredith, Ecan).

It has been observed that changing flow patterns of the Tekapo River (due to water diversion into the canal system) have changed the flow rates of the Grays River (Gabites & Horrell, 2005). However, given the lack of sites to gauge between the inflow and outflow points of the Grays River system it is difficult to verify the interaction of surface water and groundwater, and further investigation is required.

6.3.3 Comparison of Inflows and Outflows

A comparison has also been made between inflow and outflow volumes of surface water for each sub-basin. All gauging sites located on the edges of the sub-basins within the study area have been combined to give a total inflow value for each month. The outflow volumes are based on the Tekapo River gauging site and the Twizel River site (T6). The data are summarised in Table 6.2.

The results show that more surface water is leaving the Tekapo sub-basin than is being contributed at the head of the catchment. It is possible that there is a considerable amount of underflow occurring in the stream beds within the Grays River area located in the Post Glacial Alluvial Gravels; contributing a substantial volume of water to surface water flows. However, several factors have not been taken into consideration when reviewing the data such as the periodic lake water input at the head of the Tekapo River, irrigation runoff, or spring water contributions. The data suggest that in periods of higher flow volumes (>10000 l/s) that the contribution from the groundwater system is approximately 10%. In periods of low flows (<3000 l/s), the water gained from the groundwater system is in the region of 80%, which is very high. Further investigation is required to determine if this surface water/groundwater interaction within the Tekapo sub-basin is correct.

Within the Twizel sub-basin the volume of surface water leaving the sub-basin is less than the inflow volume from the head of the catchment. The decrease in flows is likely to be due to surface water contributing to the groundwater system, irrigation system water takes, or evaporation of surface water. The evaporation of surface water probably plays a major role in the decrease in volume as the lowest level of surface water outflows is in February when temperatures within the Mackenzie Basin are the highest. However, the increased irrigation levels in hotter/drier summer months are likely to also contribute to decreased water outflow levels. Determining the actual contribution to the groundwater system is difficult, but the October values do give an indication that approximately 35% of surface water flows could be contributing to the groundwater system.

Table 6.2: Summary of combined surface water inflows and outflows for each sub-basin for 3 months in the period 2007-2008.

Twizel sub-basin				
Month	**Inflow Volume (l/s)**	**Outflow Volume (l/s)**	**Difference in Flow Volumes (l/s)**	**Apparent Loss to/Gain From Groundwater (%)**
October 2007	10372	6576	3796	37
December 2007	4154	1857	2297	55
February 2008	2318	435	1883	81
Tekapo sub-basin				
Month	**Inflow Volume (l/s)**	**Outflow Volume (l/s)**	**Difference in Flow Volumes (l/s)**	**Apparent Loss to/Gain From Groundwater (%)**
October 2007	11033	12129	-1096	-10
December 2007	4983	7957	-2974	-60
February 2008	2817	5073	-2256	-80

6.4 CHAPTER SUMMARY

Prior to this study only three springs within the Mackenzie Basin were noted on Environment Canterbury's Springs Database. During the course of this study a further 53 permanently flowing springs have been located. Two primary types of springs were found: depression springs found mainly in alluvial gravels; and fracture springs within the bedrock areas. A number of the fracture springs supply a large amount of water for both domestic and farming purposes.

Concurrent river gaugings were also conducted from October 2007 until March 2008 by Environment Canterbury staff. Twenty-two sites were gauged on a monthly basis. Data from the four main rivers of the Mackenzie Basin indicate that there is a substantial interaction between the surface water and groundwater system. During the peak summer months the surface water flows are greatly reduced compared to the winter months as the contribution from snow melt to the surface water flows is less. An approximation of the volume of water moving through both sub-basins has been made and this indicates that the surface water in the Tekapo sub-basin is gaining water from groundwater. However, there may be factors which may not have been represented in this analysis. In the Twizel sub-basin a large quantity of surface water is lost to groundwater, but some may also be used for irrigation or stock water diversion, and in the summer months may also be lost to evapotranspiration. Further investigation and modelling is required to confirm the interaction of surface water/groundwater flows.

CHAPTER 7

HYDROGEOLOGY

7.1 INTRODUCTION

Collating information and defining the groundwater system within the Mackenzie Basin is important for planning and resource allocation purposes. Groundwater is the predominant source for domestic supply in the Tekapo and Twizel townships. Currently, groundwater is only used in low quantities for the purposes of irrigation and stock water supply. Generally springs, surface water and canal water supply the majority of water for farming purposes. However, existing groundwater allocation consents are currently being reviewed along with a number of consent applications. There is a call for more use of groundwater, although at this stage the resulting effects of this proposed usage on both groundwater quantity and quality is unknown.

Currently, the nature of the groundwater system in the Mackenzie Basin is generally poorly known, and the amount of recharge and groundwater storage has also not been quantified definitively. Various consultant reports, and canal construction investigations, have suggested possible groundwater quantities that may be present, as well as groundwater flow direction and depth. There are only a limited number of current drillers logs available within Environment Canterbury's Wells Database and many of the wells tend to be clustered around the townships or along the edges of the basin. Also, there are very few deep wells to provide information about groundwater at depth. There is a lack of data within the centre of each sub-basin making it difficult to accurately define the hydrogeological system. Some of the drillers logs from the canal construction period could be used to further define the system, however their spatial distribution tends to be limited to areas of the actual and proposed canal system, and generally their depth is shallow (< 30 m). Unfortunately this data was obtained late in this study and has not been incorporated here. However, historical bore logs from various sources for the entire basin are contained in Appendix 7A.

7.2 PREVIOUS WORK

The primary focus of investigations prior to the 1990's was for the purposes of canal construction. Therefore, groundwater was defined for the purposes of drainage from the dam sites, and to determine any detrimental effects that may arise from the presence of a groundwater table.

The construction of the Tekapo Dam and the Tekapo Canal in the 1940's and 1950's was completed, in a period where reporting of investigations and construction was not commonplace. Little historical information regarding the occurrence of groundwater within the Tekapo area is available apart from a number of bore logs from the 1940's and 1950's that still remain in the old records. However, an unpublished report does summarise the possible occurrence of groundwater near the Tekapo dam site. The report notes that the area to the east of the Tekapo River consists of a large thickness of Mt John Outwash Gravels (> 100 m) which is overlain by a 3-5 m thick layer of Post Glacial Alluvial Gravels. The Mt John Outwash Gravels are interbedded with lower permeability units creating impedance to the vertical infiltration of water. It is suggested that the groundwater is at least 40 m below the surface and the flow direction is parallel to the Tekapo River, following the topography of the area towards the wetlands near Grays Hills. Streams such as Edward Stream are suggested to be ephemeral in nature, and only flow following high rainfall events.

7.2.1 MacDonald (1969)

Resistivity soundings were undertaken at what is now the Pukaki Dam site by MacDonald (1969). From the soundings a deep groundwater table was inferred to be present at approximately 490 m above sea level flowing southwest beneath the Pukaki River (i.e. approximately 30 m to 60 m below the river) (Figure 7.1). It was suggested that groundwater recharge is from the southern edges of Lake Pukaki.

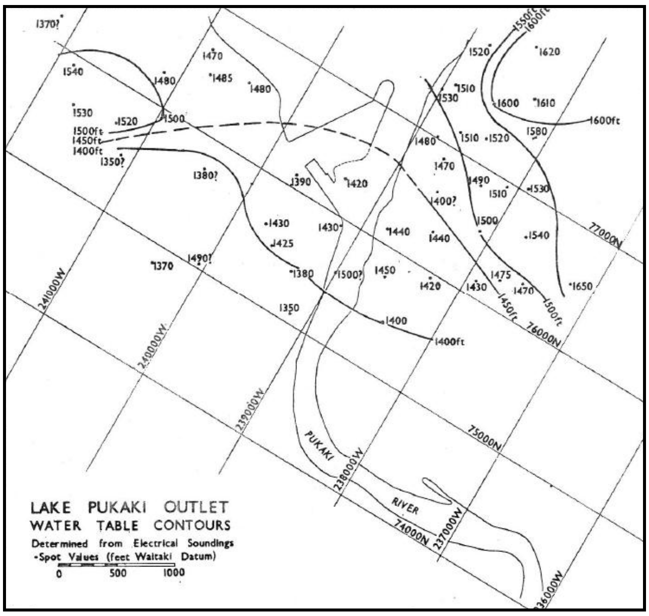


Figure 7.1: Water table contours defined by resistivity soundings near the Lake Pukaki outlet (MacDonald, 1969).

7.2.2 Read (1974)

Prior to and during the construction of the Pukaki High Dam, groundwater was reviewed during the course of geological investigations by Read (1974). Major water tables were located within the Mt John Outwash Gravels and an overlying unit known as the Contorted Sediments Gravel. It was suggested that groundwater flows downwards from the more permeable Contorted Sediments Gravel into the Mt John Outwash Gravels. Groundwater contours were drawn based on a limited amount of data, and indicate that the groundwater flow direction is towards the south (see Appendix 7F). Groundwater levels were monitored in observation wells and no seasonal fluctuation was noted. However, slightly lower levels were seen from July to December each year and were suggested to be related to changing lake levels in Lake Pukaki, but there was not enough data to confirm this. No correlation of fluctuating groundwater levels with rainfall events was observed. Several hypotheses were suggested for fluctuating groundwater levels which were:

1. A pressure system may be present where the weight of the lake water causes groundwater to rise and fall in sympathy with the lake.

2. Leakage of water from the lake bottom contributes to the groundwater system. This would require fractures of the lake sediments for water to escape or semi-permeable sediments to be present. If water was leaking at the northern end of Lake Pukaki the groundwater must travel under or around the edges of the lake bottom.

3. Groundwater is recharged from rainfall in the foothills to the west of the lake. However, it was considered that it was easier for water to flow down the Twizel River.

4. There is recharge from rainfall on or near the lake shore and flows under the dam site. It was considered to be more likely that possible recharge was from the eastern edges of Lake Pukaki and flowing around and under the lake. But in comparison to other alternatives this hypothesis is thought to be unlikely.

5. Leakage from the Tasman River to the north of the lake was also suggested. This hypothesis implies that there is a continuous or interconnected formation of permeable gravels running from the Tasman River valley under or around the edges of the lake towards the dam. The leakage system would be independent of the lake, being sealed off by impermeable sediments on the lake bottom. The time for groundwater to recharge from this source would be in terms of years.

In the area from Lake Pukaki toward Lake Ohau groundwater was thought to be present in unpredictable, random, isolated pockets within the Mt John Till, and the Mt John Outwash

Gravels were thought to contain little groundwater (Read, 1974). The area surrounding Lake Ohau was also investigated and groundwater was determined to be approximately 16 m below the mean lake level, at an elevation of 502 m. Lake Ohau is also perched by retreat deposits from the Tekapo Advance (Read, 1975).

As part of the geological investigations for the Ohau Canal, groundwater in the Glen Lyon Road area of Twizel was also reviewed by Read (1974). At the northern end of Glen Lyon Road, close to the outcrop of the Ruataniwha Fault, two groundwater aquifers were observed. An upper aquifer was noted to be present on top of and within the lower alluvial gravel unit, with the bulk of the water flowing within the upper alluvial gravels. The base of the aquifer was found at the base of the lower alluvial gravels. The thickness of the alluvial gravels ranged from 6 m to 20 m. The reason for the increase in thickness is likely to be from channels that have cut through the Balmoral Outwash Gravels, and older formations, creating an alluvial valley which was subsequently backfilled with the lower alluvial gravels. Following this deposition, the entire area is thought to have been covered by a veneer of upper alluvial gravels. If such an alluvial valley exists, the routes of groundwater movement are most likely thought to be towards the southeast in the direction of the present day Fraser Stream. If an alluvial valley is present, the valley floor is suggested to be at least 25 m below the present day surface. However, geophysical surveys or other investigations were required to confirm this hypothesis.

The groundwater levels were monitored in the upper aquifer over approximately 4 years and indicate that the water levels are reasonably steady with a yearly fluctuation where levels were at a maximum between September and December (Figure 7.2). A lower aquifer was encountered within the Pre-Balmoral Outwash Gravels (Wolds), with an insitu permeability of 10^{-6} to 10^{-7} cm/sec. The base of this aquifer was thought to be on top of the Ostler Formation (also known as the Glentanner Formation). The Ostler Formation acts as an impermeable barrier to groundwater flow underneath and to the east of the Pre-Balmoral Outwash Gravels (Wolds). However, a more permeable channel must be present for the lower aquifer to cross the Ruataniwha Fault. Inflows and seeps were commonly observed in the Balmoral Outwash Gravels indicating a higher insitu permeability compared to the Pre-Balmoral Outwash Gravels.

7.2.3 Read (1976)

Read (1976) summarises data from previous reports and notes that groundwater was recognised at least 30 m below Lake Pukaki suggesting that the lake is perched (Figure 7.3). It is also thought that groundwater is flowing preferentially through the Ice Contact Gravel unit rather than through the Mt John Outwash Gravels due to the higher permeability of the overlying unit.

The source of groundwater recharge is unknown, with no correlation seen between lake inflows, rainfall, Pukaki River flows, and groundwater levels. It was noted that the water table did not rise in conjunction with the first period of lake raising, of 6 m, in January 1976.

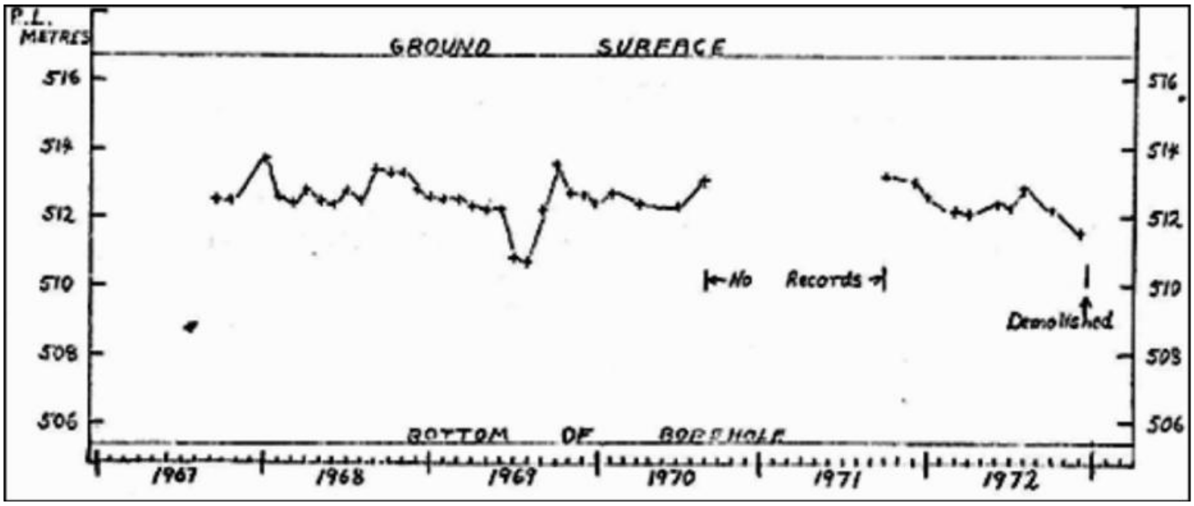


Figure 7.2: Groundwater levels monitored over approximately 4 years in the Glen Lyon Road area of Twizel (Read, 1975).

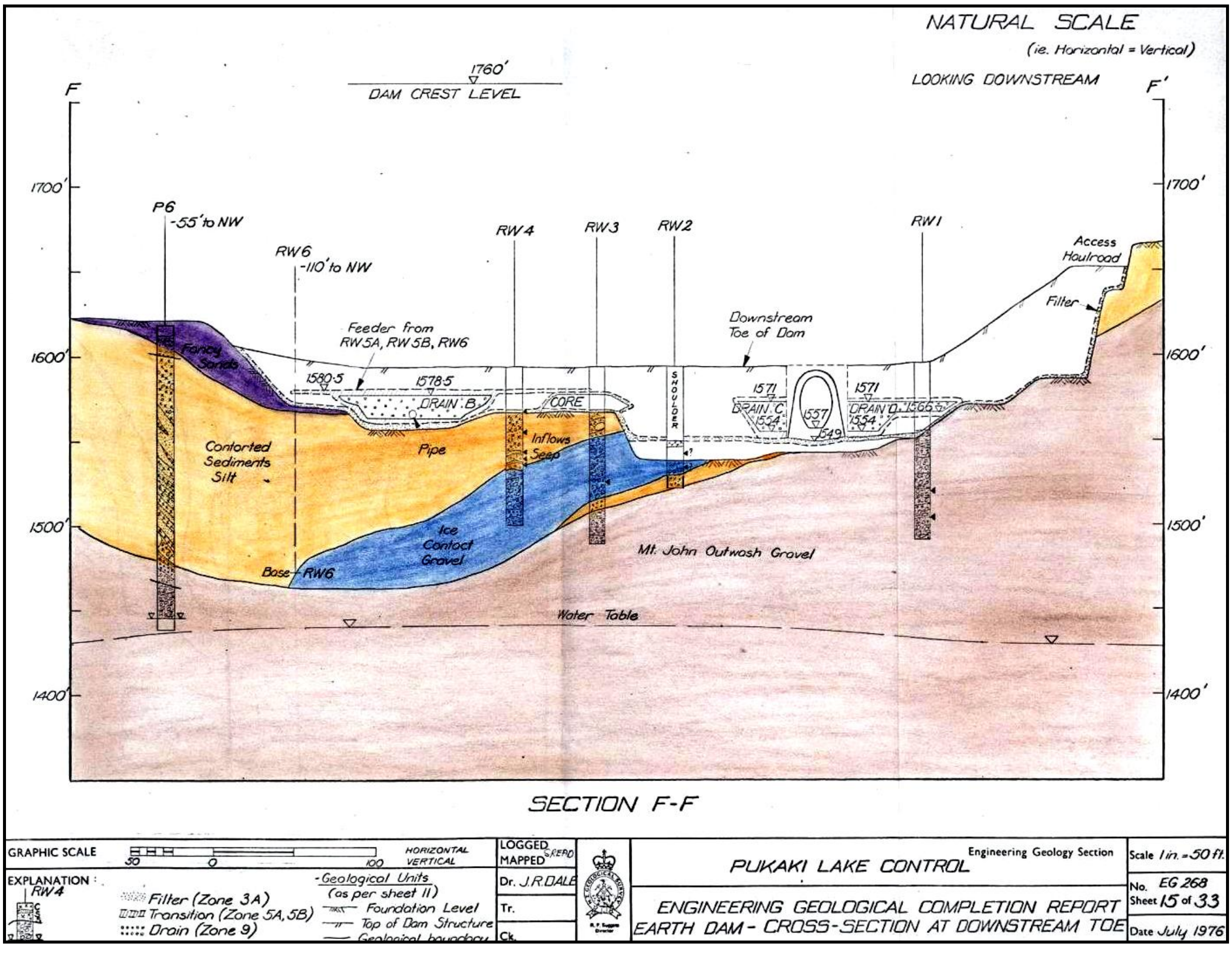


Figure 7.3: Geological cross section of the area beneath the Pukaki Dam looking south down the Pukaki River (Read, 1976).

7.2.4 Macfarlane (1981)

Groundwater was also reviewed by Macfarlane (1981) to identify any problems that may have arisen at the time of the construction of the Ohau and Pukaki Canals. Much of the information had already been summarised in Read (1974). Within the area close to the northern end of Glen Lyon Road it was noted that the shallow groundwater recognised by Read (1974) was being recharged by groundwater flow from the Ostler cut section of the Pukaki Canal, although the main recharge sources were from the Twizel River, Dry Stream, and Fraser Stream. Shallow groundwater (< 3 m) that was above foundation levels between the Twizel River and Dry Stream were lowered by development and drainage of a gravel borrow area. Water levels between the Ruataniwha Fault and the Fraser Stream were also lowered by the installation of an interceptor trench. Thirty six ‘wet areas’ were also mapped which were controlled by geological structures. The wet areas were dug out and backfilled with free draining gravels connected to the underdrainage system.

Closer to the Ohau Canal inlet, by Lake Ohau, a groundwater table was noted to be above the lake level and that fluctuations of the water levels did not correlate with lake level fluctuations. It was suggested that this water table is perched and has a recharge source in the southwest. Further investigations noted that Lake Ohau is perched and that seepages occurring along the ‘dry’ Ohau riverbed are from the main water table which occurs beneath the Ohau Canal inlet site. Groundwater contours were drawn based on measured water levels and also inferred, with a groundwater flow direction to the southeast (see Appendix 7F).

7.2.5 Waitaki Catchment Commission (1982)

The Waitaki Catchment was described in a report by the Waitaki Catchment Commission (1982). Groundwater is briefly mentioned in this report and suggests that downstream of the three glacial lakes groundwater lies at great depths, and that both the Tekapo and Pukaki Rivers are perched as the river beds are sealed off from the surrounding area by glacial silts carried by the river water. Within the Tekapo area local swamps associated with the streams and groundwater were noted close to the mouths of the Grays River, Irishman Creek, and Mary Burn. Swamps were also noted near the centre of the Twizel township.

7.2.6 Macfarlane (1995)

After completion of the Ruataniwha Dam, the Ohau B Canal, and the Ohau B powerhouse, a report was completed summarising the engineering geological aspects of the investigations and construction by Macfarlane (1995). As part of this review, groundwater in the area of the Ruataniwha Dam and associated canal system was summarised. Prior to the filling of Lake

Ruataniwha the groundwater table was interpreted to reduce in elevation towards Lake Benmore in the south with a sharp swing towards the Ohau River downstream of the Ruataniwha Dam. The predominant recharge of groundwater was from the northwest (see Appendix 7F). The bedrock on the southern side of the Ohau River provided an impermeable barrier to groundwater flow downstream of the dam. Lake Ruataniwha is underlain by Mt John Outwash Gravels, and the Ohau River had down cut into these. Further downstream two terraces formed on the north side of the Ohau River have been mapped as Tekapo Outwash Gravels (15-20 m above the river) and Post Glacial Alluvial Gravels (5-8 m above the river). Seeps and inflows were observed at discrete levels within the Mt John Outwash Gravel where permeability changes within the unit and at the basal contact with other units of lower permeability occurred. Discrete flows were noted in open gravel lenses at or below the normal river level.

Following the filling of Lake Ruataniwha a significant, rapid rise in groundwater levels were measured. Leakage from Lake Ruataniwha into the Mt John Outwash Gravels was said to have occurred, and the estimated water losses from the lake were in the order of 5 to 7 cumecs. Downstream of the dam groundwater levels only fluctuated a little, showing no real response to the lake filling, and it is suggested that there was a pre-existing barrier to groundwater flow. Springs gradually developed at discrete locations along the terrace riser on the north side of the Ohau River downstream of the dam. The surface seepage originates from a perched water table. It is suggested that the ‘main’ water table slopes beneath the lower terrace, within layers or lenses of openwork gravel with silt/clay at the base of the lens. The springs/seepages have been monitored using v-notch weirs and measured volumes of 0.6-0.7 m^3/sec, with a total outflow from the area of approximately 1.0 cumecs.

7.2.7 URS (2001)

In 2001 an engineering consultancy, URS, was engaged by the Mackenzie District Council to report on the soils and groundwater in the Twizel township area to provide information for planning decisions. The water levels of a number of wells were measured in September 2000 and February 2001. A groundwater flow direction towards the southeast was determined. It was noted that the depth to groundwater in the Fraser Stream was approximately 3 m to 4 m, and increased to a depth of 25 m further to the southwest of the Fraser Stream. There was no change in piezometric contours between the winter and summer surveys. Step drawdown tests were also carried out on the three public wells that are used for the town’s water supply. Transmissivity values were estimated for the aquifer penetrated by the three wells and ranged from 3300 m^2/day to 6800 m^2/day. The depths of the three wells are 12.2 m, 13.3 m, and 16.9 m.

7.2.8 SKM (2004)

Groundwater for the entire Waitaki Catchment was reviewed for the Ministry for the Environment by SKM consultants (Heller & Williamson, 2004), including estimates of the recharge volumes, total storage, and preliminary water balance for the Tekapo and Twizel groundwater basins. The report suggests that the upper hydraulic conductivity of the Upper Waitaki catchment ranges from 0.1 m/day to 100 m/day. For the purposes of the water balance estimates groundwater outflows have been assumed to be equal to groundwater inflows or recharge. Specific yield values have been estimated from literature values for unconsolidated, sandy, silty gravels. The large aquifer storage implies a long residence time and increased lag times in response to groundwater abstraction. Recharge values are based on values from the Lower Waitaki area and the Wanaka Basin area. It is noted that there may be limits on the availability of groundwater within the Tekapo and Twizel groundwater basins due to low hydraulic conductivity and the saturated depth of gravels.

7.2.9 White *et al.* (2005)

In a report for Meridian Energy White *et al.* (2005) reviewed groundwater occurrences throughout the area via a desk study to identify the potential effects of irrigation on water quantity and quality. The Mackenzie Basin was subdivided into multiple sub regions for calculations of groundwater recharge and net effects of irrigation. The occurrence of groundwater noted within this report relevant to the current study is summarised below.

1. The lower reaches of the Grays River rests on bedrock. The river gains flow near Grays Hills indicating that groundwater is moving to the surface in this area. Grays Hills may also cause groundwater within or close to the bed of the Tekapo River and the Mary Burn to come to the surface. In the mid plains area surface water is recharging groundwater, Irishman Creek, for example, flows beneath the ground for a substantial portion of its flow path, thereby contributing to the groundwater system.

2. There is evidence that groundwater may recharge the Pukaki and Tekapo Rivers in their lower reaches. Stony River appears to be recharging groundwater in the northeast of Lake Benmore, but in its lower reaches the river is likely to be recharged by groundwater.

3. A water balance has been estimated by averaging rainfall using 1 km by 1 km grid cells, and by using evapotranspiration data from Tara Hills to the south of the basin.

7.3 CROSS SECTIONS

Cross-sections using well logs from Environment Canterbury's Wells Database were constructed to determine if any laterally continuous water table was present, and to identify continuous lithological layers. The XSect software program from Environment Canterbury was used to create cross-sections. No clear correlations between drill holes were identified in the cross-sections; therefore the drillers' descriptions contained within the logs were reviewed individually to see if more detail could be ascertained. However, the drillers' descriptions tend to be brief and describe material from wells drilled using rotary drills. Often rotary drills crush the material, so that much of the lithological changes between units that may be present at depth are not seen by the driller. Another factor reducing the quality of the drill logs is that each of the glacial outwash gravel units are very similar to each other and are hard to differentiate.

As an example, cross-section A–A' was created running southeast to northwest through the Twizel township. The location of the cross-section is shown in Figure 7.4, and the cross-section is shown in Figure 7.5. It shows the difficulty in defining the lateral extent of units, but does indicate that water bearing channels will be isolated and unconnected. The cross-section does indicate a decrease in water levels further away from the Fraser Stream area, suggesting that the active river bed area is perched and/or that there may be other discontinuous water tables present at a greater depth. Not all of the logs have a water level shown, as this information is not contained on the drillers log and these wells were inaccessible for monitoring during the study period. A cross-section for the Tekapo sub-basin has not been created due to the lack of well logs for that area. All available well logs for the study area held in Environment Canterbury's Wells Database are contained in Appendix 7B.

Figure 7.4: Location of cross-section A – A' (Grid ref: A = 2277394 5655041 and A' = 2275881 5659446).

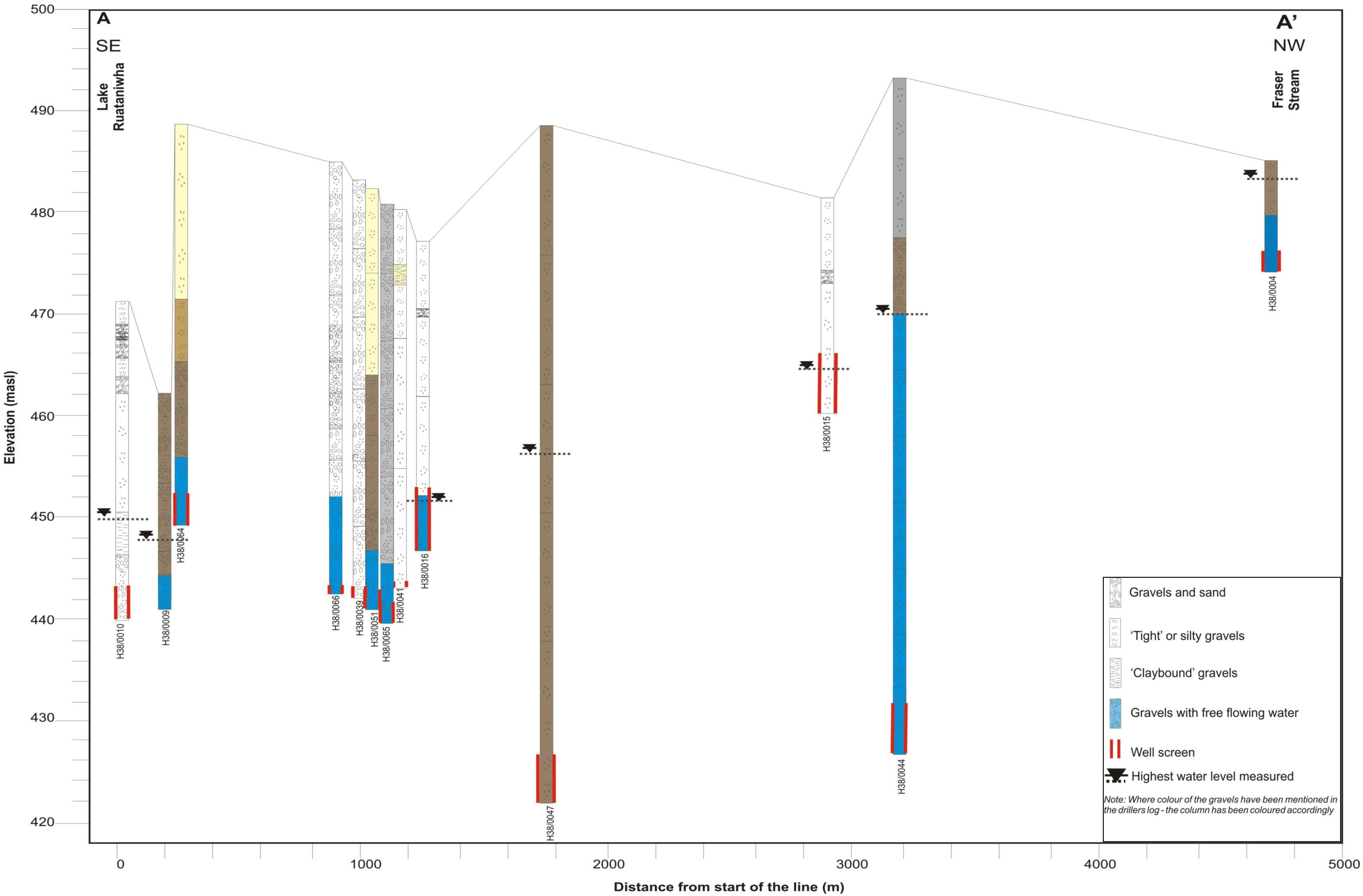


Figure 7.5: Cross-section A – A' running southeast to northwest through Twizel.

7.4 PERMEABILITY AND SIEVE ANALYSIS

Ideally permeability tests should be carried out on subsurface lithological formations to determine the possible occurrence of groundwater. However, insitu testing in glacial outwash gravels can be difficult, and laboratory tests are generally not representative as the sorting and compaction of the unit is lost when the sample is removed from the site. Permeability tests were undertaken during the canal construction period and the results are summarised in Table 7.1. To increase understanding of which glacial formations would be more likely to carry groundwater, samples were collected from various locations for sieve tests as part of this study. The process of sieving provides information on the percentage of fines (silts and clays) compared to coarser material. Only one sample was collected from each site and as these were obtained from the surface they are likely to have been affected by weathering processes. Ideally a large number of samples from each location should be tested to determine the average fines content for each formation. The small sample size and method of sampling does create a bias in the results. Large scale sieve analyses were undertaken during the canal construction period, and the results from some of these tests are contained in Appendix 7C.

The results of the sieve tests done for this study are shown in Appendix 7C. Sieve tests were also carried out on lenses of silt/soil within gravel units for comparison (Appendix 7C). The results indicate that the outwash gravels have a lower silt/clay percentage, and the Mt John Outwash Gravels have the highest content of coarse material. The till samples have a lower coarse material percentage and the Balmoral Till has the highest percentage of fine material. The lenses within the formations also have a much higher fines percentage than the gravels, which creates lenses of less permeable material within the gravel formations.

Table 7.1: Summary of the percentage of fines and permeability values for the formations present within the basin (modified from Macfarlane, 1981).

Formation/Unit	Mean Gravel %	Mean Sand %	Mean Silt %	Mean Clay %	Natural Moisture Content (%)	Permeability (cm/s)	Comment
Alluvial Gravel	84	13	3		3	0.0087	Tested in lab
Tekapo Outwash Gravel	84	12	4		2.6	0.00607	Tested insitu
Mt John Outwash Gravel	81	14	5		3.2	0.0174	Tested in lab
Balmoral Outwash Gravel	77	15	7		6.1	0.00000022	Tested in lab
Interglacial Unit - silt band	1	30	64	5	19.4	nm	(fully saturated insitu)
Pre-Balmoral Outwash Gravel (Wolds)	68	20	7	5	11.2	0.00000231	Tested in lab
Glentanner Formation	49	29	15	7	8.7	nm	Tested in Lab

**nm = not measured*

7.5 SPECIFIC CAPACITY

The specific capacity is used to define the productivity of a well and is calculated by the yield of the well divided by the drawdown (Fetter, 2001). Specific capacity is often expressed in the units litres/second/metre. A higher specific capacity value indicates a more transmissive lithological unit.

The specific capacity in comparison to well depth was plotted for the wells in the study area to identify correlations (Figure 7.6). The small amount of data plotted (32 values) over such a large area is insufficient to define the presence of aquifers. However, it does suggest that the specific capacity and yield of deeper wells is less than for shallow wells. It appears that there is a decrease in specific capacity below approximately 50 metres depth. It should also be noted that the data are only from drillers logs where the wells have been pumped for a short period (less than a few hours) to develop the well, and therefore the results may not be representative. If a pump test was conducted over several days, it is possible that a much larger drawdown and recovery rate would be recorded, and therefore the well would have a lower specific capacity. The specific capacity values have also been plotted spatially across the Mackenzie Basin where information is available, and these are shown in Figure 7.7.

The specific capacity values are lowest in wells within or close to the glacial moraines and are highest in wells close to or within the active riverbeds of the Fraser Stream and Twizel River. Values range from 0.1 to 30 l/s/m. As most of the data has been collected from wells within the Twizel area a specific capacity map of this area is shown in Figure 7.8.

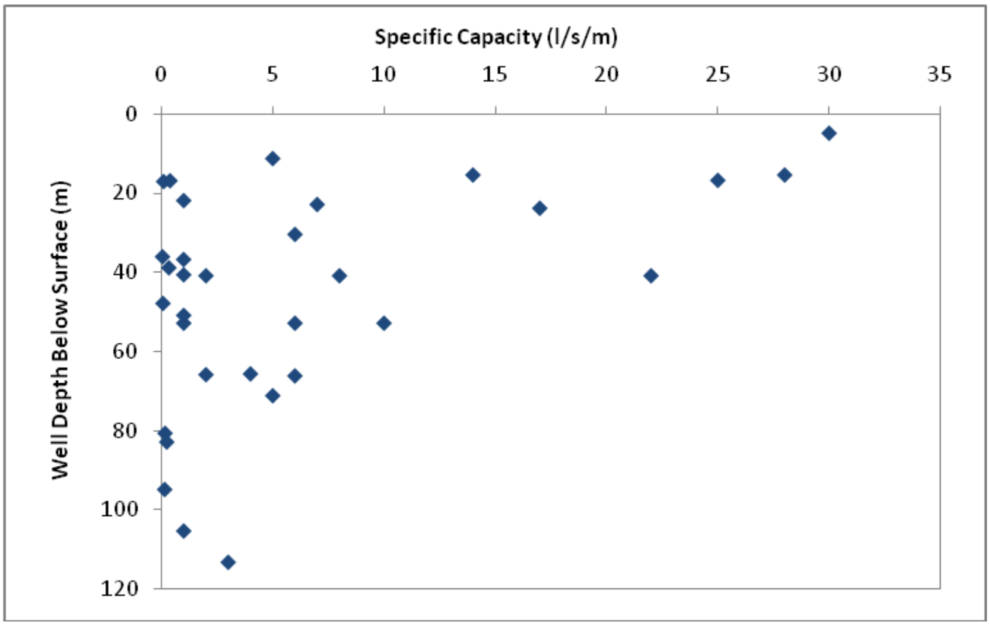


Figure 7.6: Specific capacity versus well depth for wells within the study area.

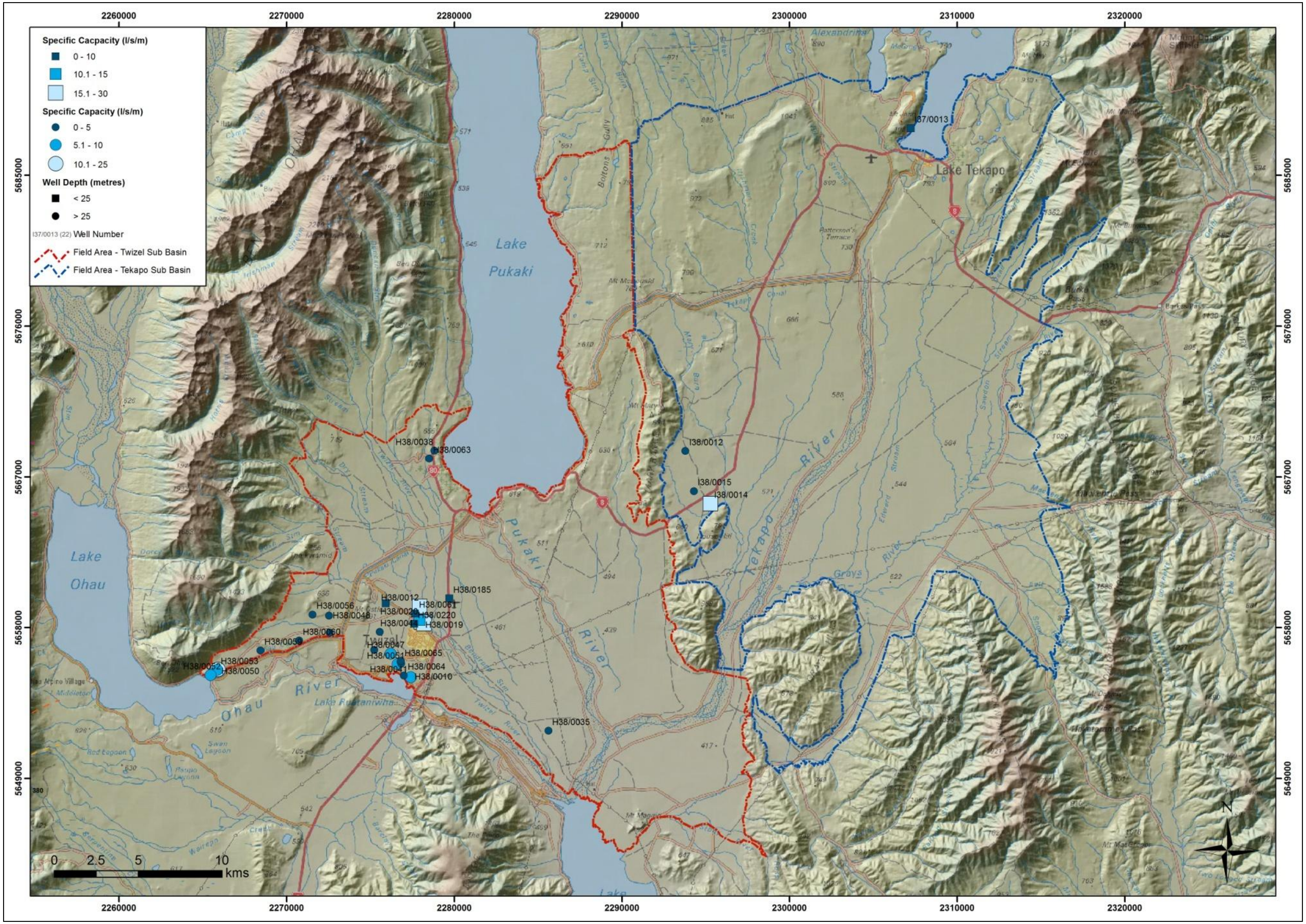


Figure 7.7: Specific capacity plotted spatially across the study area. Values have also been divided between wells less than and greater than 25 m deep.

Figure 7.8: Specific capacity values surrounding the Twizel township, where most of the wells with yield and drawdown information are located.

7.6 TRANSMISSIVITY

Transmissivity values provide an estimate of possible groundwater production. Transmissivity is a measure of the rate at which water flows through a unit width by the full saturated thickness of the aquifer at a hydraulic gradient of one. However, this assumes that flow through the aquifer will be horizontal, which is often not the case (Fetter, 2001). Transmissivity can be calculated using the specific capacity values of a well using a number of different equations such as that proposed by Theis (1963). However, this equation requires information on the period of pumping of the well, and this information has not been available for all of the wells within the study area. Therefore, the Bal (1996) equation has been used to determine transmissivity values within the study area. Bal (1996) defined a linear regression relationship between transmissivity and specific capacity values from over 3,800 wells within the Canterbury Plains area. Although the lithology within the Mackenzie Basin is not exactly the same as the Canterbury Plains, it is similar enough that the equation can be used to give an approximate idea of transmissivity values. The calculated values are contained in Appendix 7D.

The spatial distribution of transmissivity is shown in Figure 7.10. Again, as most of the data has been derived from the Twizel area a map showing the distribution of transmissivity is given in Figure 7.11. The calculated values range from 17 m^2/day to 7711 m^2/day. Similarly to specific capacity, transmissivity is lowest within the glacial moraines (H38/0038 and H38/0063), and highest within or close to the active riverbeds (H38/0012, H38/0018, and H38/0019). Another well with a high transmissivity is located within the Tekapo sub-basin near the Mary Range. I38/0014 is 23.95 m deep and has a transmissivity of 4470 m^2/day. Nearby wells that are much deeper (119 m and 80.8 m) have transmissivities of 294 m^2/day (I38/0012) and 51 m^2/day (I38/0015). The two deeper wells are located in the Balmoral Outwash Gravels whereas I38/0014 is very close to an alluvial fan. However, aerial photographs of this area indicate that wells I38/0012 (119 m deep) and I38/0014 (23.95 m deep) may be located within a buried outwash channel as the surface topography clearly shows an abandoned channel (Figure **7.9**). It is suggested that there is more groundwater flowing through the upper part of this buried channel creating a higher yield for I38/0014. An alternative possibility is that the transmissivity of the nearby alluvial fan is contributing to the groundwater supply for I38/0014 rather than the Balmoral Outwash Gravels. It is also possible that wells H38/0010, H38/0044, H38/0045, H38/0047, and H38/0051 have intercepted a buried outwash channel at depth as their well locations at the surface have a near linear pattern from northwest to southeast. They are also surrounded by wells with much lower transmissivity values, but with similar well depths. This suggests that the buried channels are laterally continuous.

A comparison can be made to transmissivity values determined for the Orari shallow aquifer system, an area to the south of the Mackenzie Basin within the foothills of the Canterbury Plains. The Orari area is comprised of two large alluvial fans. High transmissivity values were found close to or within active river beds or in abandoned river channels. Lower transmissivity values were found in more consolidated deposits and in areas where buried swamp deposits are present (McEwan, 2001). Table 7.2 summaries the transmissivity and storativity values found in the Orari area for comparison with the Mackenzie Basin values.

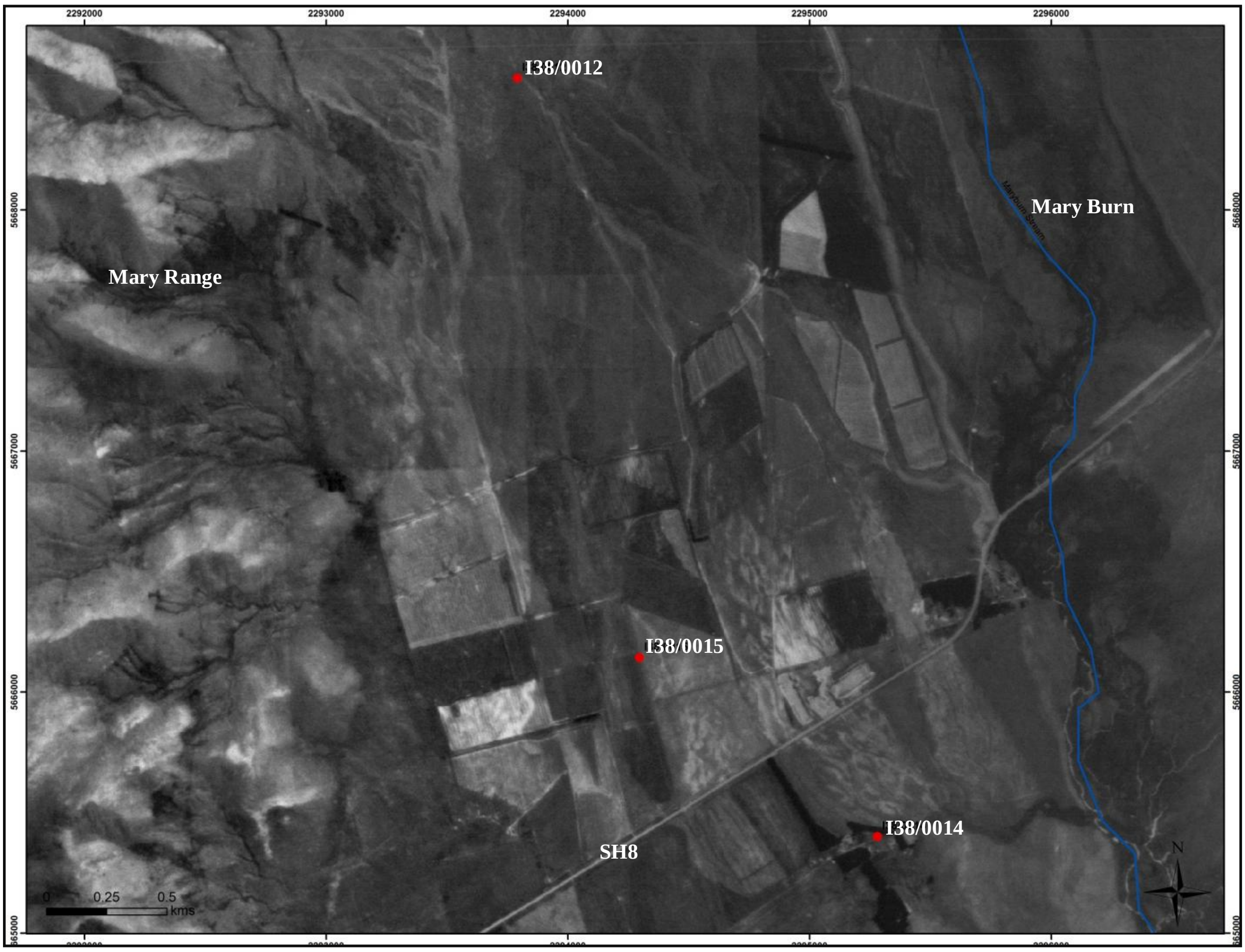


Figure 7.9: Aerial photo of the wells close to the present day Mary Burn (blue line). The red dots are wells I38/0012, I38/0015, and I38/0014 (from north to south). Braided, abandoned stream channels of the Mary Burn on the surface are evident. Well I38/0012 is located within an abandoned channel of the Mary Burn.

Table 7.2: Summary of transmissivity and storativity values of the Orari area (McEwan, 2001).

Zone	Area	Approximate Transmissivity (m^2/day)	Approximate Storativity (m^2/day)	Aquifer Type
1	Orari River and Coopers Creek Gravels	~6000	0.2	Unconfined
2	Upper Ohapi and Upper Clandeboye	~4000	0.08	Unconfined – semi confined
2b	Lower Ohapi and Lower Clandeboye	~100 – 500	0.0005	Semi confined – confined
3	Dobies, Raukapuka, Worners	~3000	0.05	Unconfined
4	Upper Coopers Creek	~2000 – 5500	0.01	Unconfined – semi confined

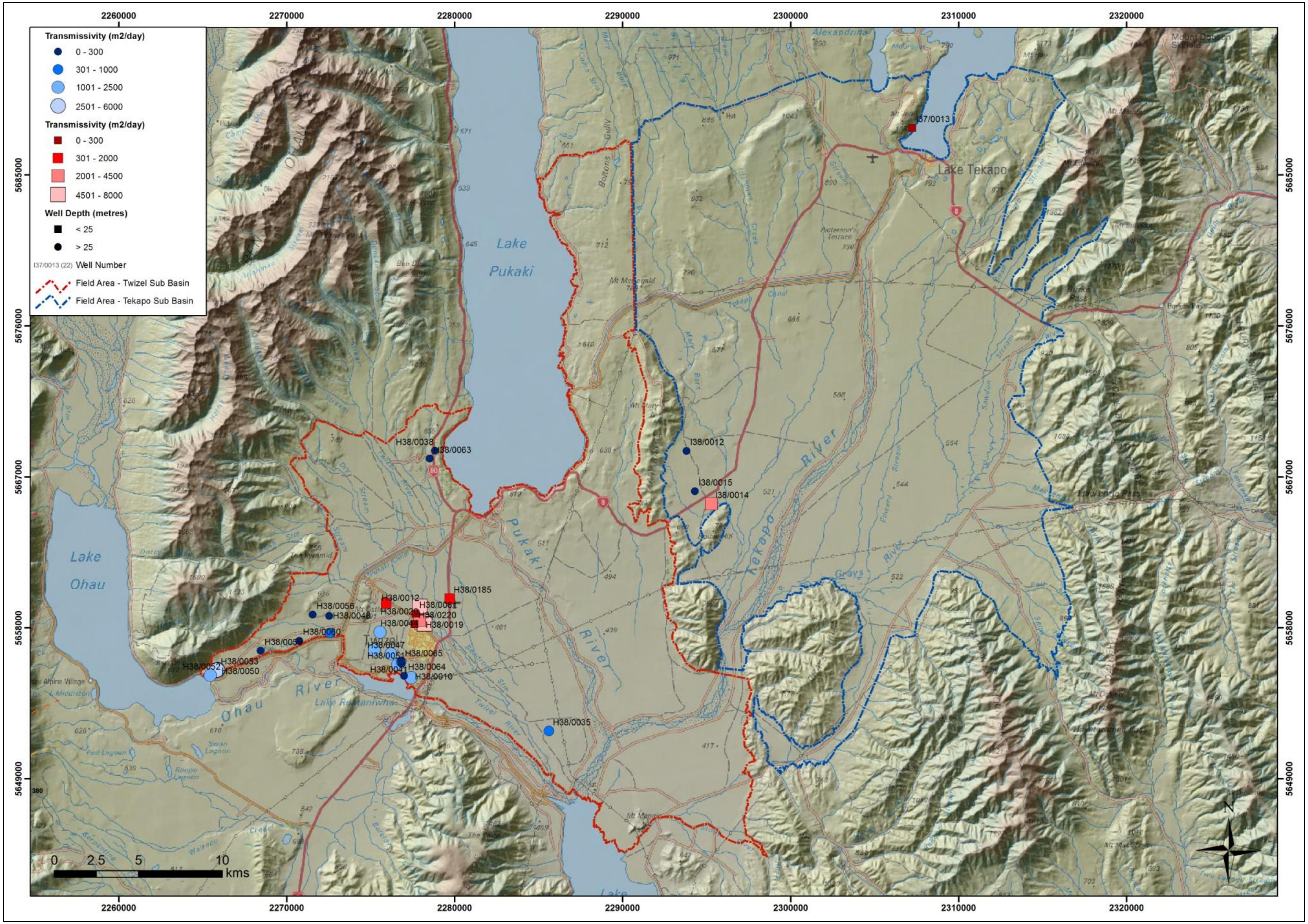


Figure 7.10: Spatial distribution of calculated transmissivity values throughout the Mackenzie Basin. The values have been divided by depth (less than and greater than 25 metres deep).

Figure 7.11: Spatial distribution of transmissivity values within the Twizel area.

7.7 GROUNDWATER FLOW DIRECTION

Piezometric surveys were conducted for wells that were accessible during February and September 2007. 42 wells were surveyed in February 2007 (Figure 7.12) and 47 in September 2007 (Figure 7.13). The data used for the piezometric contouring is contained in Appendix 7E. Not all of the same wells were measured for both surveys, as some wells were located after February 2007 and other wells had become unavailable for water level measurement in September 2007. The number of wells for the survey is low, and therefore contours have been drawn for all wells without taking into consideration well depth or whether the water level being measured is from unconfined, semi-confined, or confined aquifers. Freeze & Cherry (1979) note that drawing contour lines for groundwater levels is essentially only valid for horizontal flow in horizontal aquifers, and that such conditions are only met in aquifers that have higher hydraulic conductivities than those in confining beds. No consideration is taken into account for any vertical flow that may be occurring. However, for a generalised overview of groundwater flow direction the contours do serve a purpose and it has therefore been assumed that the aquifers are homogeneous and isotropic for the purposes of defining the groundwater flow direction.

The direction of groundwater flow is indicated by arrows which are perpendicular to the contour lines. There are large areas that have been noted as having insufficient data and therefore contour lines are grouped around areas with water level data. It should also be noted that the water levels in some of the Ministry of Works observation pipes may be questionable, as it is uncertain as to whether these wells are actually detecting a genuine water level as these types of observation pipes often ‘silt up’ at the base retarding water flows.

The two piezometric surveys were conducted at different times of the year to determine any seasonal variations in groundwater flow direction. However, no such variation was identified. In the Twizel sub-basin the direction of flow is towards the southeast where Lake Benmore is located. In the Tekapo sub-basin the direction of flow is to the southwest towards the Mary Range and the Tekapo River as it passes between the Mary Range and Grays Hills. Generally, the groundwater flow appears to follow the topographic surface. As the amount of data used to create the contour map was limited, the information has been compared to groundwater contour maps created during the canal construction period by Read (1976) and Macfarlane (1981) around Lake Pukaki and the Ohau River. These previous maps are included in Appendix 7F for comparison. The groundwater flow directions defined by Read (1976) and Macfarlane (1981) are similar to those determined in the current study.

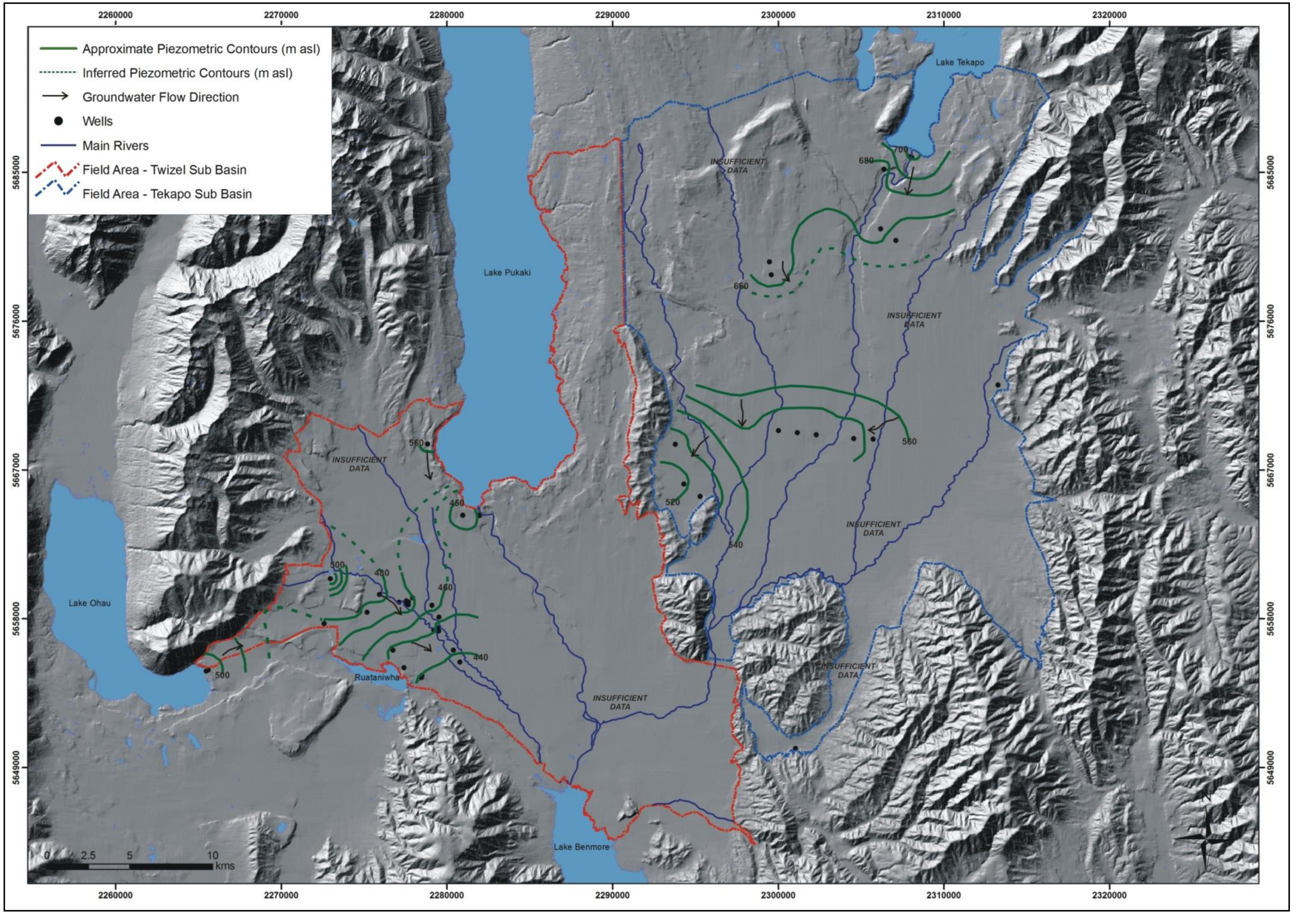


Figure 7.12: Piezometric contours (10 m intervals) for February 2007. Arrows indicate groundwater flow direction.

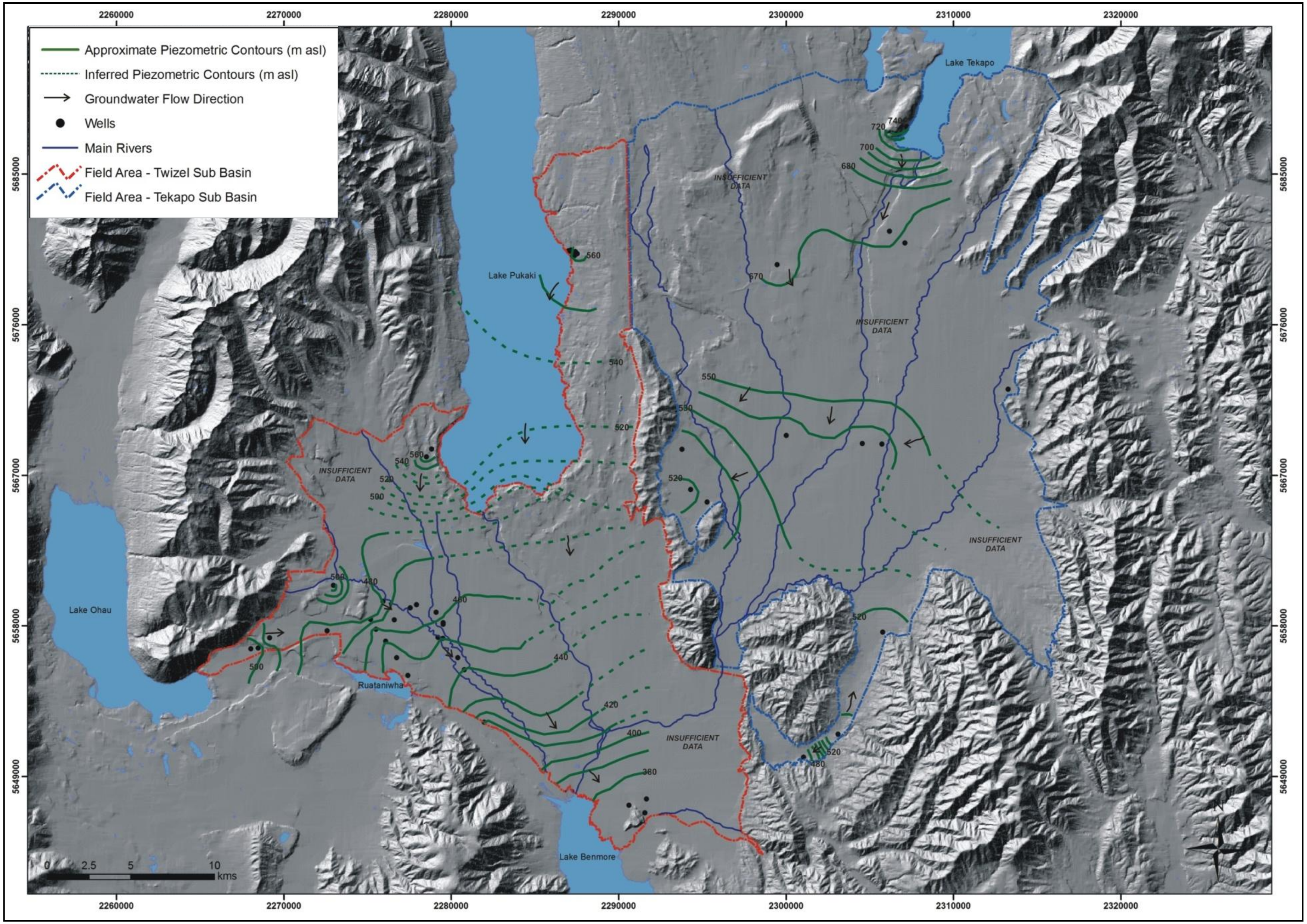


Figure 7.13: Piezometric contours (10 m intervals) for September 2007. Arrows indicate groundwater flow direction.

7.8 GROUNDWATER FLUCTUATIONS

7.8.1 Measured Responses

Over a 12 month period water levels were monitored on a monthly basis in 46 wells throughout the Mackenzie Basin. The locations of wells monitored on a regular basis along with other wells present within the basin are shown in Figure 7.14. The water level data and graphs for each well are contained in Appendix 7G.

In addition to monthly monitoring eight data loggers measuring water levels every 15 minutes were installed. Five loggers were installed in March 2007 in the Tekapo sub-basin in wells I38/0003, I38/0012, I38/0045, I38/0050, and I39/0005. A further three loggers were installed in the Twizel sub-basin in June 2007 in wells H38/0010, H38/0030, and H38/0057. The location of data collection points for all of the hydrographs are shown in Figure 7.15. Barometric pressure loggers were also installed within the Twizel and Tekapo sub-basins. In confined aquifers changes in barometric pressure will be reflected by changes in water levels, therefore barometric pressure data can be used to indicate whether or not aquifers are confined or unconfined.

The data from the water level data loggers has been used to create hydrographs with corresponding monthly water level readings, rainfall, barometric pressure, and river gauging data. The hydrograph for the Mary Burn group is shown in Figure 7.16. The remaining hydrographs are contained in Appendix 7H. The hydrograph shown in Figure 7.16 is a good example of the minimal groundwater level fluctuations seen throughout the Mackenzie Basin. The exceptions to this trend are in those wells close to the Twizel River and the foothills to the east of the Tekapo sub-basin. When comparing both monthly and 15 minute interval water level data in the deeper wells (generally those greater than 25 m deep) with rainfall and river flow data it is apparent that there is no relationship. This suggests that groundwater is not directly affected by rainfall events or flows within nearby rivers and streams.

Rainfall events tend to be high intensity and of short duration and it can be seen that the Mary Burn responds to these rainfall events indicating a correlation between rainfall and surface water flows. It is likely that either the soil surface does not allow rapid rainfall infiltration and that the runoff to the streams is great, or that rainfall is infiltrating the surface but the compact, glacial lithology at depth greatly decreases the vertical infiltration rate and therefore no immediate response of groundwater levels at depth can be seen corresponding to rainfall events. This implies that recharge rates are very low and corresponds with the specific capacity and transmissivity for wells I38/0012 and I38/0015. It also corresponds with the age of the groundwater which is in the region of 92 to 115 years for well I38/0015.

No correlation is seen between groundwater levels and barometric pressure suggesting that the aquifer is not confined. However, all other data would suggest that the aquifer is at least semi-confined.

In wells close to the foothills of the Rollesby Range and Grampian Mountains, within the Tekapo sub-basin, groundwater levels did fluctuate over the year both in manual readings and in the data from the water level data logger in well I38/0003 (Grays Flats Group – see Appendix 7H). The fluctuations correspond with rainfall events recorded at Glenrock Station near the Mackenzie Pass. This suggests that groundwater is derived from rainfall near the tops of the ranges in this area, and that the shallow groundwater is moving west down through the large alluvial fans in the Mackenzie and Hakataramea Passes.

Further away from the ranges, close to the east side of the Tekapo River, a water level data logger was installed in well I38/0050 (Grays Flats Group). This well is a Ministry of Works observation pipe, approximately 25 m deep. There are no pumping wells nearby and the area is not irrigated. The data logger shows fluctuations that are thought to correlate to rainfall in the ranges to the east and shallow groundwater that is flowing through the large fans of the Mackenzie Pass and Hakataramea Pass towards the Tekapo River. It is also possible that the well is encountering subsurface flows of the Edward Stream; the dry stream channel is approximately 1 km to the east of this well. The rainfall at the head of the Edward Stream catchment could be providing ‘pulses’ of water flows. It was noted that often the results of large rainfall events at the head of the catchment were not seen for up to six months at the southern end of the Edward Stream and Grays River confluence, as they appear again on the surface north of Grays Hills, before flowing west towards the Tekapo River (M. Urquhart pers. comm., 2007). The water level data logger in well I38/0050 has recorded very sharp influxes of water, with a slow dissipation afterwards. It has also been suggested that the Grays River system (including Edwards Stream) is hydraulically linked to the Tekapo River (Gabites & Horrell, 2005). It is possible that periods of high flows (lake spilling) in the Tekapo River could contribute to the ‘spikes’ in groundwater levels. The transmissivity in this area is likely to be very low; however the very quick increase of the water level cannot be adequately explained at this stage and requires further investigation.

Another water level data logger was installed in I39/0005 (Haldon Group – see Appendix 7H), which is approximately 68 m deep. The water levels stayed constant throughout the year at a depth of approximately 5 m below the ground surface. The very regular, but small, fluctuations seen in the water level data logger are possibly due to fluctuations in Lake Benmore as the lake level rises and falls in response to inputs of canal water. Again there is no correlation with rainfall events or barometric pressure in well I39/0005. There is a downwards spike seen in the monthly water levels of I39/0007 and this is likely to be due to pumping having ceased just before the well was measured. Both I39/0004 and I39/0005 do not have pumps installed.

Groundwater levels in shallow wells near or within the active river bed of the Twizel River show a reaction to changing rainfall levels and river flows. However, the river gaugings that were conducted manually on a monthly basis by Environment Canterbury staff only began in October 2007, and therefore there is not a long term record to make a definite correlation. The water level data logger in well H38/0030 (Bendrose Group – see Appendix 7H), close to the Twizel River, does show fluctuations in the recorded data, however this well is also a pumped well and the data is not particularly representative of natural fluctuations. The wells in the active river bed are likely to be closely related to river flows, and it is expected that this would be reflected in longer term data. This suggests that the groundwater in this area is unconfined and is possibly a perched, unconfined groundwater table. Again, no correlation with barometric pressure was seen, further suggesting an unconfined water table within this area.

Deeper wells further away from the Twizel River and Fraser Stream area show much less significant correlation to rainfall. The water level data logger in H38/0010 (Tussock Bend Group – see Appendix 7H) shows very little fluctuation over the period that data was recorded. There is no apparent relationship to barometric pressure suggesting that groundwater is either unconfined or semi-confined.

The water level data logger installed in H38/0057 (Manuka Terrace Group – see Appendix 7H) does appear to show some seasonal change. However this well had a pump for stock water installed in November 2007, and it is likely that this is the cause of the variation. The effects of regular pumping can be seen later in the recording period and on closer examination, the average time taken for water levels to return to their original, pre-pumping levels is approximately 14 hours. Not enough is known about the period of pumping for each event to define the transmissivity values in this area, but it would appear that it does take groundwater levels a substantial period of time to recover from pumping events.

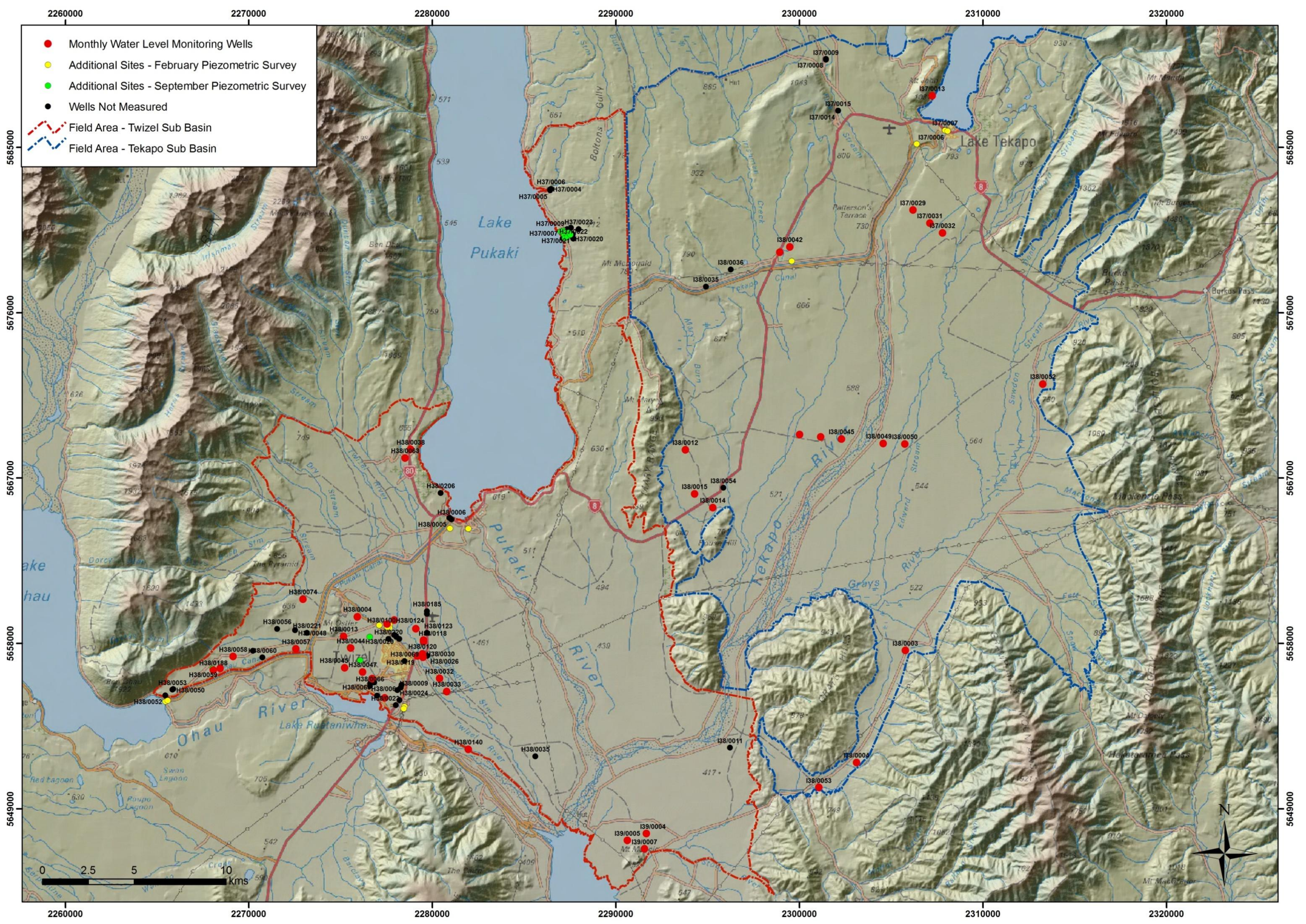


Figure 7.14: Locations of wells monitored monthly, additional wells used for the February and September piezometric surveys and other wells that are present within the Mackenzie Basin but inaccessible for the purposes of this study.

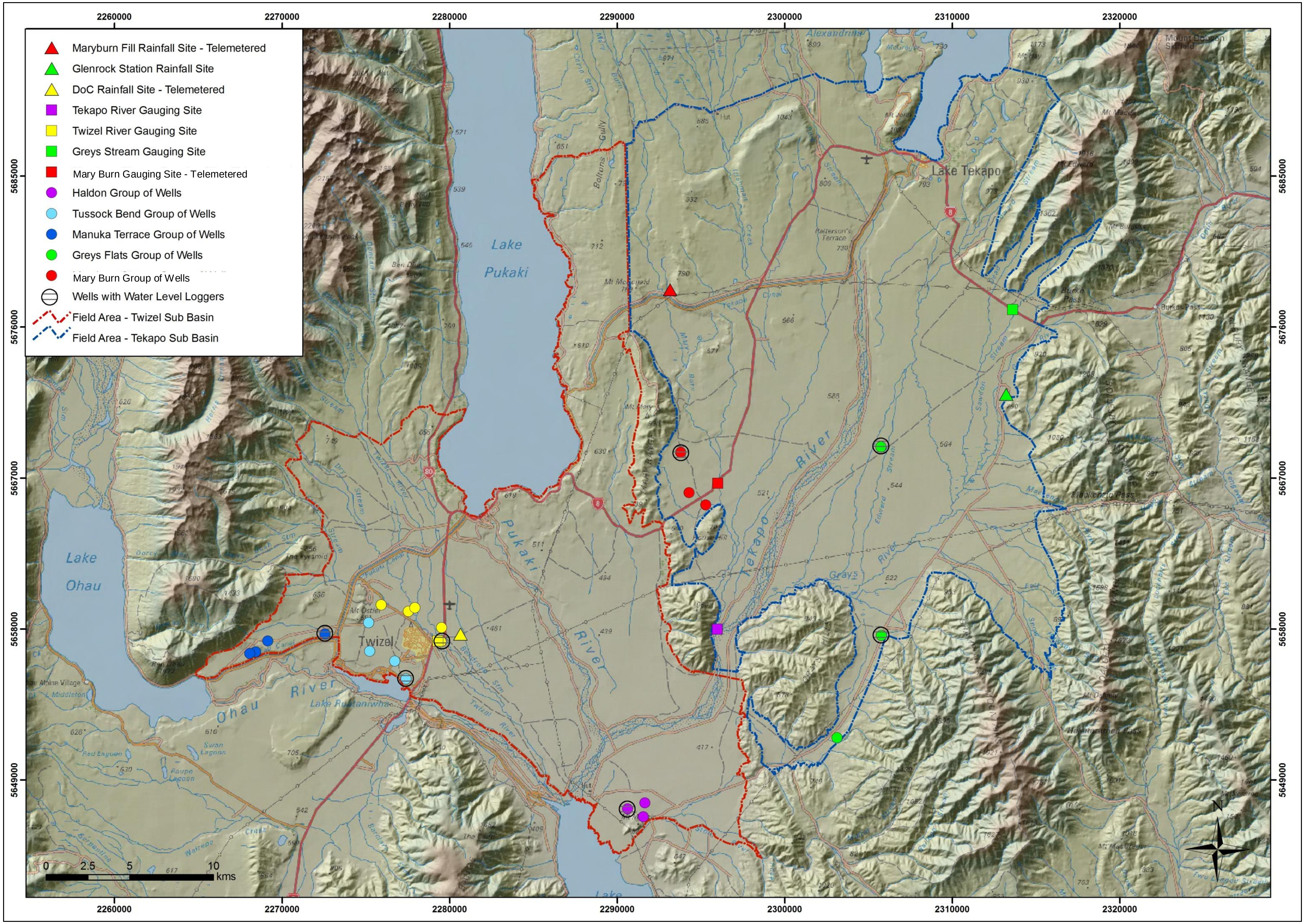


Figure 7.15: Location map of wells and recorder sites in the Mackenzie Basin for various hydrographs. Groups of data are represented by similar colours.

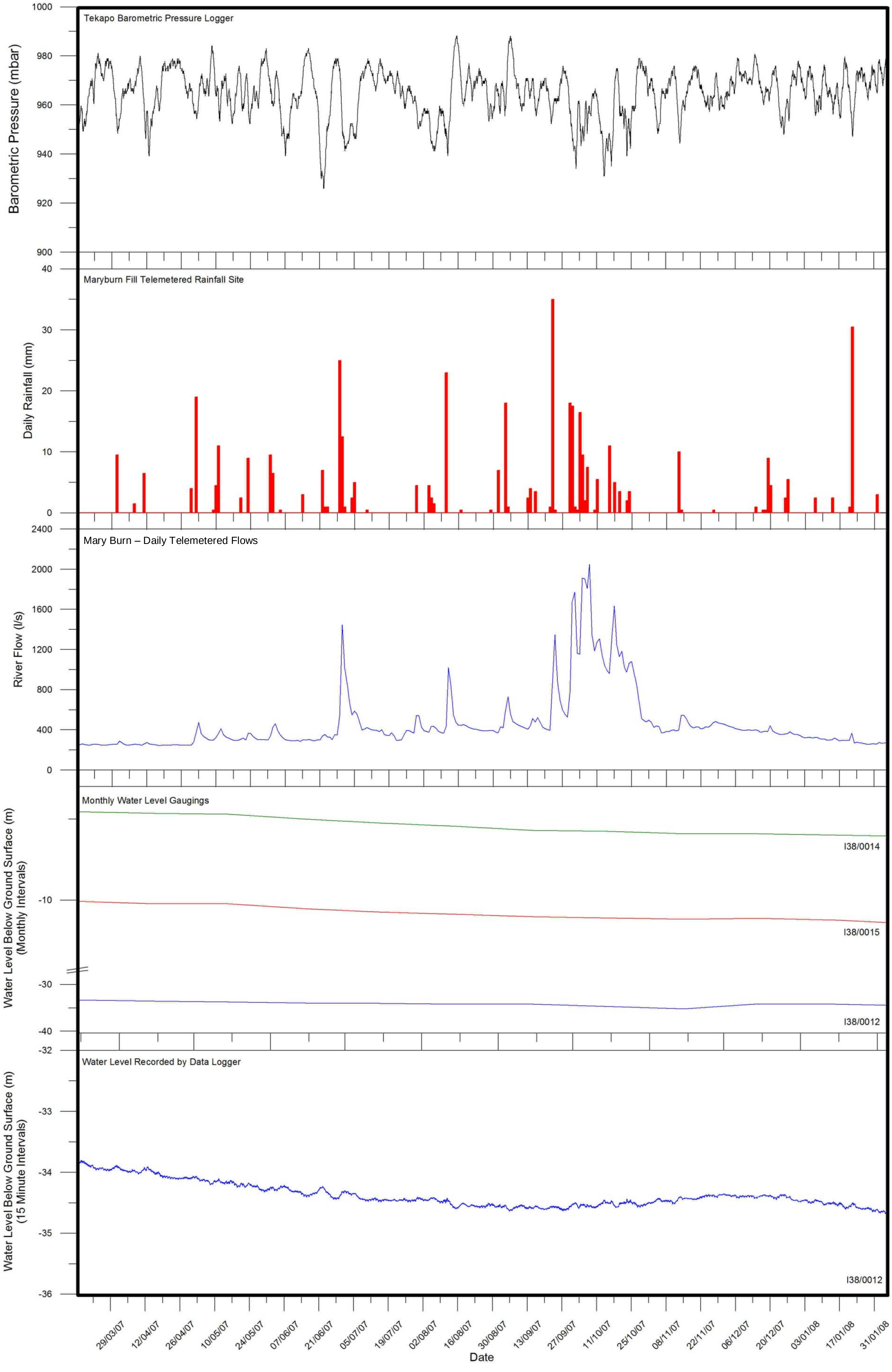


Figure 7.16: Hydrograph for wells within the Mary Burn Group in the Tekapo sub-basin. The location of each recorder site is shown in Figure 7.15.

7.8.2 Seasonal Fluctuations

Seasonal fluctuations of groundwater levels are generally not seen in the well data and this particularly evident for the deeper wells (>25 m deep). The wells close to the eastern ranges are the only wells that exhibit any seasonal fluctuations. In the water level data logger data for well I38/0003 water levels increase in the winter period and are highest in August and September. This is similar to rainfall trends for multiple rainfall sites within the Tekapo sub-basin and also correlates to spring snow melts which increase surface water flows.

7.9 GROUNDWATER OCCURRENCE

7.9.1 Water Tables

On the basis of data collected during this study, and from historical data, it is suggested that there are three general groundwater systems present within the Mackenzie Basin. A deeper, semi-confined aquifer is present in both the Tekapo and Twizel sub-basins which does not respond to river flows, rainfall events, or barometric pressure changes. However, this deeper ‘aquifer’ (>25 m depth) is not likely to be laterally continuous, and instead is likely to be present in isolated lenses and layers at varying depths, most probably within the Mt John Outwash Gravels. A shallow, unconfined water table is present within, or very close to, active river beds that respond to river and rainfall fluctuations. This shallow water table is most likely to occur within the Post Glacial Alluvial Gravels Formation. A third type of groundwater occurrence is within the large alluvial fans within the foothills of the eastern ranges of the basin, as well as smaller fans on the sides of the Mary Range, and also probably on the Ben Ohau Range. The groundwater within the alluvial fans is shallow and responds to rainfall events.

The recharge sources for each of these groundwater systems are complex. Permeability, both horizontally and vertically, needs to be considered for each system. The glacial geology of the Mackenzie Basin reduces the amount of permeability in both directions. The three types of systems and factors affecting each are summarised below. A conceptual representation of the suggested shallow and deep groundwater system is illustrated in Figure 7.18.

7.9.2 Deep Groundwater System

It is suggested that groundwater flows preferentially within the Mt John Outwash Gravels within both the Tekapo and Twizel sub-basins. The Mt John Outwash Gravels have a lower silt/clay content and also contain layers and lenses of sorted, openwork gravels. It is thought that the lenses of gravel have silt/clay at the base that decreases the downwards infiltration of groundwater into underlying units. From the available drilling logs it could not be determined if the lenses and layers were connected and continuous. However, if the buried channels and lenses are compared to the present day abandoned surface channels, it is possible that they are connected and flow is horizontally continuous. Once buried, it is also possible that these channels have been reworked by overriding ice and glacial outwash rivers, disconnecting the braided system at depth. The depth of the deep groundwater system is likely to be variable both laterally and vertically due to the variable nature of outwash gravel deposits and from re-working by subsequent glacial processes. Accurately determining the location of the deep groundwater system for the purposes of abstraction could be difficult.

Older glacial formations such as the Wolds and Balmoral Formations are likely to retard groundwater flow and infiltration. As these glacial deposits are the two oldest within the Mackenzie Basin they are more weathered as well as compressed due to burial from subsequent glacial advances. However, Macfarlane (1978) noted that groundwater was present within the Balmoral Outwash Gravels to the west of the Pukaki Canal near Twizel, where ponding and saturated ground conditions were present following high rainfall events. Two wells are located within the Balmoral Outwash Gravels (I38/0012 and I38/0015), but the low yields from these wells has made them of no use for farming purposes. Their close proximity to the Balmoral moraine may also play a part in low yield values. The lack of water level fluctuations over the 12 months recorded by the water level data logger in I38/0012 suggests that the Balmoral Outwash Gravels have a very low permeability (K_H of 10^{-4} to 10^{-5}).

The moraines present, both at or near the surface and buried at depth, are also likely to greatly reduce horizontal and vertical permeability. Rainfall in the moraine areas is prevented from infiltrating vertically and surface and groundwater flows from the north of the study area will also be greatly reduced. However, there are wells present within the Tekapo and Mt John moraines on the west side of Lake Pukaki, but the specific yield and transmissivity for the wells are very low in comparison to wells further south (H38/0038 and H38/0063). The restriction of horizontal flow by moraines can also be seen south of the Maryburn Fill area of the Tekapo Canal. Multiple springs are present to the south of the present day swamp which resides in the site of a pro-glacial lake (just south of the Maryburn Fill – 2293811 5674743). Surface water moves through this area, where the Mary Burn has incised through the Balmoral moraine to enable flow to the south. However, groundwater flow is probably restricted causing the formation of springs that contribute to the swamp water.

All three major glacial lakes are perched on fine deposits from both glacial retreat deposits and lake sediment from gravity settling. These deposits seal the bottom of the lake preventing leakage to groundwater.

7.9.3 Shallow Groundwater System

The Post Glacial Alluvial Gravels provide a highly permeable unit for groundwater movement, and enable easy infiltration of surface water. The Post Glacial Alluvial Gravels contain the shallow, unconfined water table present in the Twizel area. Rainfall at the head of the Twizel River and Fraser Stream, in the Ben Ohau Range, is likely to move directly through the river system and out towards Lake Benmore without contributing significant quantities of water to the deeper groundwater system. The shallow groundwater is thought to be perched on the lower alluvial gravels which have a higher silt/clay content than the upper alluvial gravels, and/or perched on lower permeability units such as the Mt John and Balmoral Outwash Gravels. There is likely to be some downwards leakage from the Post Glacial Alluvial Gravels supplying some recharge to the deeper groundwater. Near the centre of the Twizel township, between the Twizel River and the Fraser Stream, the area is very swampy. Groundwater is present approximately 2 m below the surface, again suggesting a perched groundwater system in this area. The man-made Lake Ruataniwha also contributes to the groundwater system. At the time of filling, leakage from the lake was observed leading to an increase in groundwater levels in the surrounding area. It was also noted that springs 'popped up' from the ground in multiple areas in the Twizel area at the same time (T. Allan pers. comm., 2007). This suggests that the gravels to the north and west of Lake Ruataniwha are more permeable (K_H of 10^{-1} to 10^{-2}), or that connected gravel lenses or layers are present, and that water losses from the lake contribute to the shallow groundwater system.

In the Tekapo sub-basin, the Post Glacial Alluvial Gravels are also present. Close to the junction of State Highway 8 and the Tekapo Canal, groundwater is very close to the surface (<3 m), and has been observed during this study to rise up to the surface in gravel pits during periods of high rainfall. This suggests that the shallow groundwater is recharged directly by rainfall, but given the close proximity to the head of the stream catchments there is unlikely to be much differentiation between stream and rainfall recharge of shallow groundwater. Parts of the Irishman Creek are ephemeral, but flows occur along most of its reach during very high rainfall events. Two reaches of the Irishman Creek, north of State Highway 8 and just to the north of the Tekapo River, flow all year round indicating that the creek does contribute to the shallow groundwater system in the area between State Highway 8 and the Tekapo River.

Grays River and Edward Stream are other examples of rivers with ephemeral reaches. The rivers flow to the north of State Highway 8, disappear below ground, and reappear a few kilometres north of the bedrock high of Grays Hills. There is likely to be a substantial amount of shallow groundwater flowing between these two points, although probably moving very slowly (see Grays Flats Group hydrograph – Appendix 7H). The presence of this shallow groundwater table was also observed by farmers digging an irrigation gallery, where a hard rock ‘pan’ was encountered approximately 5 m below the surface, and that water flowed from above this layer down into the trench (A. Shearer pers. comm., 2007). It is likely that the ‘pan’ was a hard layer of loess or a change in lithology from the Post Glacial Alluvial Gravels to the underlying Mt John Outwash Gravels. It has also been noted that recharge for the shallow groundwater may also be from canal leakage which has been observed and noted in historical reports.

7.9.4 Alluvial Fan Groundwater System

The third type of groundwater system is also shallow but present within the alluvial fans that surround the Mackenzie Basin and on the sides of the Mary Range. The large fans on the Hakataramea Pass and Mackenzie Pass allow rainfall at the top of the ranges to move down towards the west. The supply is sufficient for one farm to extract adequate quantities for irrigation and stock water. It was commented that digging holes approximately 1 m deep within the fan area supplied sufficient water for the stock (N. Phillips per. comm., 2007). Numerous springs at the base of the fans, along the west side of Haldon Road, are present where the fan encounters a change in lithology and permeability, bringing the groundwater to the surface. It is likely that some of this groundwater continues to flow at depth westwards towards the Tekapo River. Well I38/0014 is also located very close to an alluvial fan on the side of the Mary Range, and the yield and transmissivity of this well are very high compared to surrounding wells. However, the age of the water sample from this well is fairly old (>100 years) suggesting that this well is possibly drawing its water from a mixture of the alluvial fan and the underlying Balmoral Outwash Gravels.

7.9.5 Flowing Artesian System

Springs within the bedrock areas are also supplying a substantial amount of groundwater recharge. The well that supplies the Mt John Observatory (I37/0013) is a good example. The flowing artesian well is thought to derive its water from rainfall infiltrating the fractures of the bedrock of Mt John. The well is a flowing artesian type probably due to the head generated by the water infiltration at a higher elevation in the bedrock. Springs can also be seen coming to the surface within the bedrock at a higher elevation than the well. A number of flowing artesian wells are also located on the east side of Lake Pukaki, north of the Tekapo Canal outlet. The wells are located in the Tekapo moraine. It is thought that these wells are of a flowing artesian type due to the confining nature of the lateral moraine and that groundwater and surface water flows are present to the east of this location at a higher elevation than the wells. It is possible that the volume of groundwater in this area may be quite high as the rainfall and surface water flows in the area are high. However, due to the lateral moraine lithology it is likely that rainfall and surface water do not infiltrate downwards and instead runoff into Lake Pukaki. Further investigations in this area are required.

7.9.6 Effect of Faults

The fault systems present within the Mackenzie Basin represent impermeable groundwater flow barriers (see Figure 2.11 for map of faults within the Mackenzie Basin). The Irishman Creek Fault, for example, cuts off horizontal water flows from the north as the movement of the fault has brought the more impermeable Glentanner Formation to the surface. Only incision through the fault by the Irishman Creek allows surface flows, and therefore to some extent groundwater flows, to move from the far north of the basin towards the south. The Ruataniwha Fault (part of the Ostler Fault Zone) also forces water flows to move in a south easterly direction towards Lake Benmore for the same reasons.

7.9.7 Aquitards

Aquitards are present throughout the Mackenzie Basin varying both laterally and with depth. The aquitards are likely to be derived from till material and lake sediment deposits. Further to the south these types of deposits will be present where fines moving through the braided outwash river system have settled out, sealing off the base of gravel channels which are then subsequently buried. However, much of the fines will have been moved much further south through what was the Benmore Gorge (now Lake Benmore) to the southeast. Therefore, wells such as H38/0035 and I39/0005 are in gravels that are much more sorted than those closer to the terminal moraines, but have a reduced silt/clay content as this material has been washed away even further to the south. These wells are likely to be high producing wells.

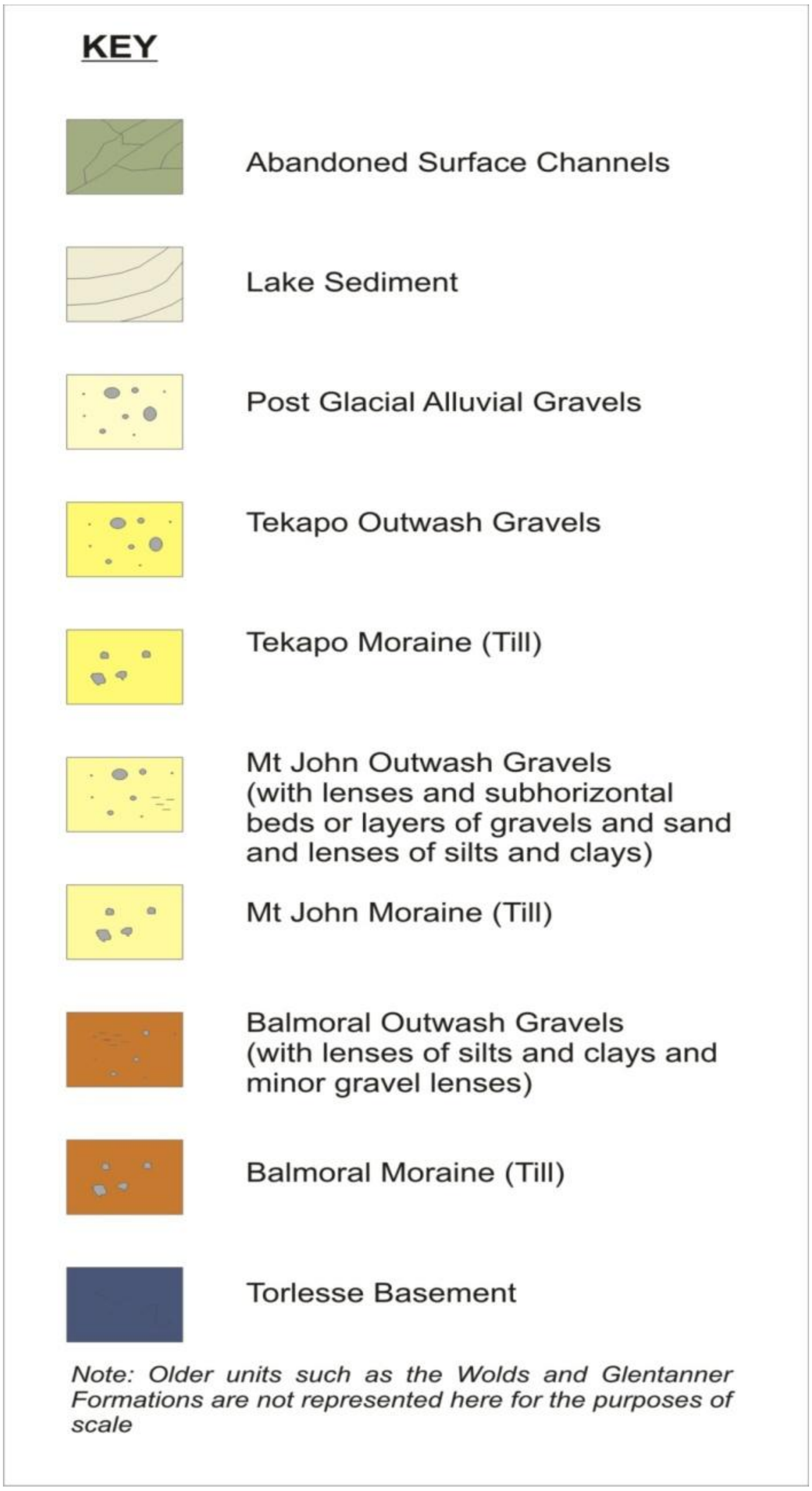


Figure 7.17: Key for the conceptual block model contained in Figure 7.18.

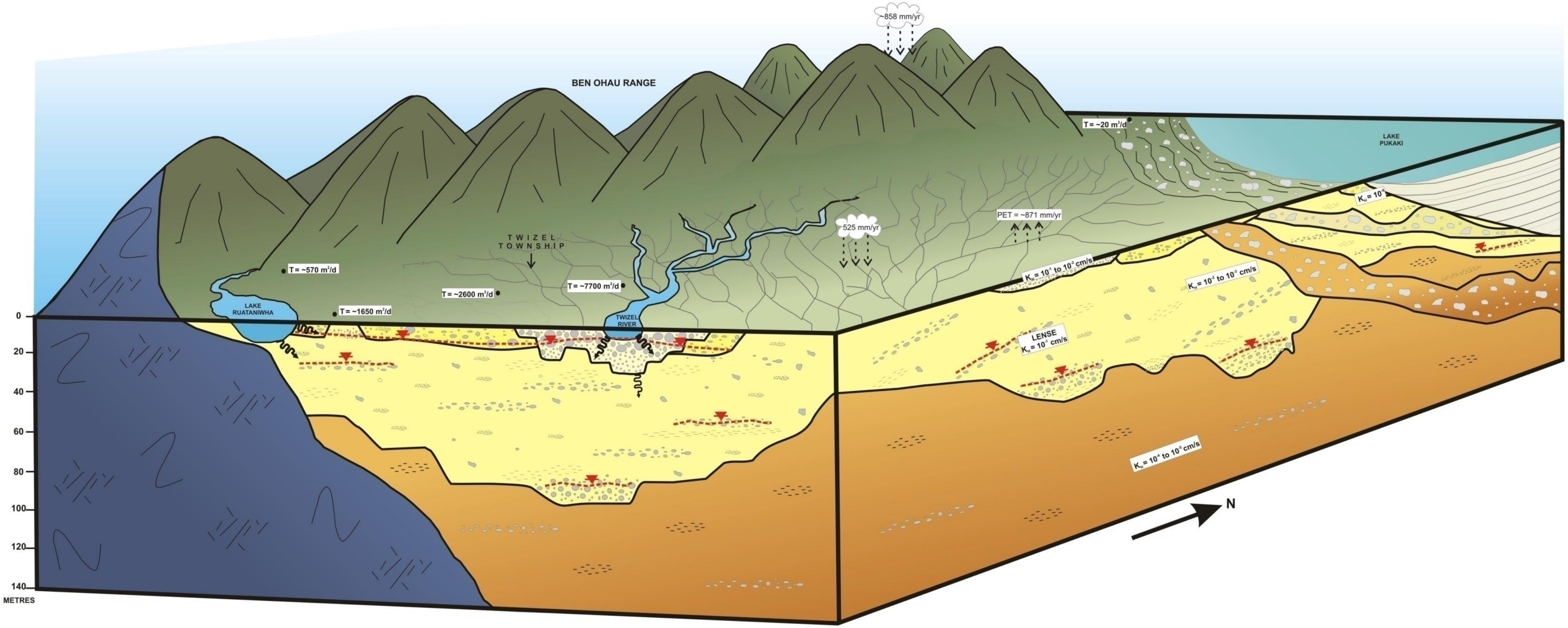


Figure 7.18: Conceptual representation of the possible groundwater system of the Mackenzie Basin. The Twizel sub-basin has been used as the basis for the model as there is insufficient data for the Tekapo sub-basin to make a definitive interpretation. The calculated transmissivity values for a selection of wells are indicated by 'T', the values were calculated using the Bal (1996) equation. The horizontal permeability values (K_H) shown are based on values observed by Read (1976) and Macfarlane (1981, 1995). The potential evapotranspiration is an annual average of 50 years of data from the Tara Hills climate site to the south of the Mackenzie Basin as there is no evapotranspiration rates recorded within the study area. The rainfall rates are based on annual averages from rainfall measurements collected in Twizel and at Braemar Station.

7.10 WATER BALANCE

Two studies (Heller & Williamson, 2004; White *et al.*, 2005) have estimated the quantity of groundwater and the potential storage capacity the Mackenzie Basin. The results presented in these reports have varied due to the different estimations of input values. Both studies determine similar order of magnitude recharge rates of 0.82 and 0.89 m3/s for the Tekapo sub-basin, with greater variation (0.87 and 0.58 m^3/s) for the Twizel sub-basin (see Table 7.3 and Table 7.4). The surface area values used for infiltration of rainfall is also different for both of these studies. White *et al.* (2005) has removed areas of mapped as moraine as possible rainfall infiltration areas. A preliminary water balance has been attempted as part of this study, but it became clear that there are several unknown or uncertain parameters.

Table 7.3: Summary of values estimated for the Tekapo and Twizel groundwater basins (Heller & Williamson, 2004).

Zone	Aquifer Surface Area (km^2)	Estimated Average Specific Yield	Estimated Average Saturated Thickness (m)	Total Storage (Mm^3)
Tekapo	644.7	0.2	20	2579
Twizel	685.1	0.2	20	2740
Zone	**Surface Area (km^2)**	**Infiltration Rate (m/yr)**	**Recharge (Mm^3/yr)**	**Recharge (l/s)**
Tekapo	644.7	0.040	25.8	817
Twizel	685.1	0.040	27.4	868

Table 7.4: Summary of values estimated for the Tekapo and Twizel groundwater basins (White *et al.*, 2005).

Subregion	Average rainfall (mm/yr)	Area of zone (ha)	Rainfall (Mm^3/yr)	Rainfall (m^3/sec)	Estimated rainfall recharge (m^3/sec)
2 (Tekapo)	601	41835	251.4	8	0.89
4 (Twizel)	520	23203	120.7	3.8	0.58

Using the mean annual potential evapotranspiration (PET) and mean annual rainfall data from the Tara Hills climate site which is located in Omarama 30 kms south of the study area, net rainfall recharge of 93 mm/yr has been estimated (Table 7.5). The mean annual PET for Tara Hills is 871 mm/yr (based on data from 1951 to 2007), and the mean annual rainfall is 518 mm/yr for the same period. The PET rate is higher than the rainfall rate for eight months of the year, (see Figure 1.4 in Chapter One) and therefore rainfall is only greater than PET, leading to recharge, for the months May to August. The rate of infiltration at Tara Hills is approximately 58%, without taking into account runoff or soil moisture holding capacity.

The Twizel sub-basin has not been estimated as the rainfall data for the Twizel area is insufficient and covers a smaller period of time compared to the Lake Tekapo climate site. If this same percentage (58%) is used for rainfall data collected during the same period at the Lake Tekapo climate site, a recharge of approximately 125 mm/yr is estimated based on mean rainfall for the months May to August of 217 mm/yr. However this figure makes the assumptions listed below:

- Groundwater/surface water inflows and outflows are the same
- There is no leakage from the canal system that could contribute to groundwater
- The infiltration rate is constant across the basin, which is unlikely as vegetation and surface materials do vary across the basin
- There is no surface runoff of rainfall, which is known to be incorrect
- All of the net rainfall (after evapotranspiration) is infiltrating the ground surface
- There is no infiltration of surface water into the subsurface through river bed seepage is occurring
- Rainfall is constant across the basin, which is not the case as observed during this study
- Rainfall events are uniform, which is not the case as intense and sporadic rainfall events have been observed during this study.

Table 7.5: Net recharge to groundwater – Tara Hills data from 1951 to 2007 (data source: Niwa, 2008).

Month	May	June	July	August	Total
Mean Potential Evapotranspiration (Tara Hills) (mm)	20	9	11	26	67
Mean Rainfall (Tara Hills) (mm)	46	42	34	38	160
Rainfall minus Potential Evapotranspiration (mm)	26	33	23	11	93
Recharge Percentage	56	78	69	30	**58**

It is concluded that there are presently too many unknown or variable input parameters to reliably estimate annual recharge to groundwater in the Mackenzie Basin. To be able to better quantify the recharge rate and amount of storage within the Mackenzie Basin more data is required for PET rates within the basin, rainfall runoff rates, stream leakage, and the soil moisture holding capacity. Also, spring flows and inputs from irrigation infiltration needs to be defined, especially potential canal losses.

7.11 CHAPTER SUMMARY

Over the past 50 years groundwater has been investigated within the Mackenzie Basin primarily for the purposes of determining problems that groundwater may create for canal and dam construction. Therefore there is not a large historical detail of groundwater occurrence, but over the last 10 years groundwater has been reviewed more closely by various consultants as the requirement for groundwater abstraction increases.

During this study cross-sections were generated using bore logs from Environment Canterbury's Wells Database, but no strong correlation between lithological units and groundwater levels could be defined. Groundwater levels were seen to decrease away from the Fraser Stream in Twizel in the cross-section contained within this chapter (Figure 7.5) and this suggests either a perched stream system or two separate groundwater systems.

A small number of lithological samples were collected for sieve testing to determine the amount of fines within each formation. The small sample size leaves the results open to interpretation, but it can be seen that the glacial tills and silt lenses within the outwash gravels have a much higher fines content compared to the outwash gravels. The results were compared to similar tests done during the construction of the Ohau and Pukaki Canal system. The findings were similar between the sets of results from the historical work and the current study.

The specific capacity values for each well were plotted both with regard to well depth and spatially. The values used to calculate specific capacity may not be accurate as they are from short duration pump tests done when developing the well. However, there is an indication that shallow wells close to active river beds have higher specific capacity values and will therefore be higher producing wells. Transmissivity values were also calculated using the Bal (1996) equation, and these indicate that shallow wells close to the active rivers have a much higher transmissivity. The lowest values were found in wells located in moraines.

Piezometric contours, based on a limited amount of data, indicate that the groundwater flow direction in the Twizel sub-basin is to the southeast. In the Tekapo sub-basin the direction is to the southwest. Both flow directions are towards Lake Benmore in the south. The piezometric contours drawn based on data collected during this study are similar to those drawn for the Twizel sub-basin in the 1970's and 1980's.

Groundwater level data collected both manually and by water level data loggers have been plotted over time and against rainfall, barometric pressure, and river flows. In deeper wells there is no apparent correlation to rainfall, barometric pressure, or river flows, suggesting that the low permeability of the glacial lithologies does not allow rapid horizontal or vertical hydraulic conductivity to occur. In wells close to the active riverbeds fluctuations in groundwater levels were observed and these appear to correlate with river flows. In areas close to the ranges and alluvial fans, fluctuations corresponded well with rainfall events suggesting that these wells are recharged by rainfall.

From data collected during this study, and from a review of historical data, it is suggested that there are three types of groundwater systems present within the Mackenzie Basin. A deep groundwater system is present within the Mt John Outwash Gravels and occurs mainly in clean, gravel lenses and layers. The location of this groundwater both vertically and laterally is likely to be highly variable. It is unknown whether the groundwater system is connected at depth. A shallow groundwater system occurs in the Post Glacial Alluvial Gravels in both the Tekapo and Twizel sub-basins. This highly permeable unit is likely to be moving groundwater through the system fairly rapidly and out into Lake Benmore. It is unlikely that this shallow groundwater system contributes a large amount of water to deeper systems via downwards leakage. In the large alluvial fans on the eastern side of the basin a secondary shallow groundwater system is also present. The alluvial fans carry rainfall infiltration from the top of the ranges down towards the west.

A water balance was attempted as part of this study, but due to many unknown factors it is difficult to clearly quantify the recharge and storage capacity of the Mackenize Basin. Further investigations and data collection are required to accurately determine the groundwater resource available at depth.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 THESIS SUMMARY AND CONCLUSIONS

The primary objectives of this study were to explore the hydrogeology of the Mackenzie Basin, to review pre-existing information, and gather new baseline data for future, more in depth, groundwater investigations. As part of the data collection a conceptual hydrogeological model has been created as the basis for further work. The estimation of the quantity and distribution of groundwater throughout the Mackenzie Basin has not been as successful due to the limited amount and distribution of data for the area.

8.1.1 Geology

The basement of the Mackenzie Basin is formed by the Torlesse Terrane. Uplift due to the nearby Alpine Fault led to erosion of greywacke and semi schist providing sediment for accumulation during the Pliocene and Quaternary. The depression which is now the Mackenzie Basin was formed from folding and faulting that occurred during the Kaikoura Orogeny. During the Late Miocene to the Early Quaternary the Glentanner Formation was deposited, followed by a series of glacial and interglacial periods. The four main glacial formations from this period are the Wolds, Balmoral, Mt. John, and Tekapo ranging in age from > 300 ka to ~16 ka.

The Torlesse bedrock outcrops in the ranges surrounding and within the Mackenzie Basin. The impermeable and low permeability barriers of the bedrock and the Glentanner Formation outcrop within both the Ostler Fault Zone near Twizel and the Irishman Creek Fault near Lake Tekapo. The compaction and lithology of the Glentanner Formation suggests that this formation is the hydrogeological basement for the area. The overlying older glacial formations (Wolds and Balmoral) are also less permeable relative to the overlying younger formations of the Mt John and Tekapo. Changes in lithology and permeability also occur within formations between the moraine deposits and outwash gravels. The moraines create areas with a higher silt/clay content, less sorting of gravels, and lower permeabilities. It has been difficult to define the type and extent of the highly complex glacial formations at depth and their effect on the hydrogeological system. However, based on investigations carried out during the canal construction, it is suggested that the Mt John Outwash Gravels have been reworked and sorted creating lenses and layers of clean, openwork gravels that may create groundwater flow paths.

The complexity at depth is illustrated by the complex nature of the abandoned outwash channels that can be seen on the surface as a pattern of dissected, dendritic drainage channels. As the rivers have continued to down-cut through the glacial deposits terraces of varying elevation are present throughout the area. The Post Glacial Alluvial Gravels which surround the present day rivers and streams have a low silt and clay content and are likely to provide an easy flow path for a shallow groundwater system.

8.1.2 Geophysics

Three geophysical surveys were conducted during the course of this study within the Tekapo sub-basin. The purpose of the surveys was to approximate the depth to basement, the thickness of the glacial gravels, and to determine if any aquifers were present at depth. The three different methods have proven to be useful for their respective purposes and similar surveys should be conducted within the Twizel sub-basin to create a complete picture of the Mackenzie Basin.

8.1.2.1 Gravity

A gravity survey was carried out from west to east along a 22 km line in the centre of the Tekapo sub-basin. The models created from the data collected suggest that the depth to the Torlesse basement is approximately 1000 m in places, and that the topography of the basement is variable. The model indicates that the sub-basin is divided into a further two buried sub-basins. However, gravity modelling is a non-unique process and several models do fit the same data. The results need to be interpreted based on other survey models and geological knowledge. Further surveys may need to be conducted to confirm the results from this study.

8.1.2.2 Time-domain Electromagnetics (TEM)

A TEM survey was run along the same line as the gravity survey to enable the results of the two surveys to be compared to further the interpretation. The data from the survey was of good quality and the depth of penetration was up to 300 m in places. The data clearly indicate two changes in resistivity within the subsurface. However, given the nature of the lithology, where glacial deposits have a high clay content, it is difficult to determine whether the decreasing apparent resistivity values with depth indicate the presence of groundwater or the presence of an increasing clay content within the glacial formations. Drilling a well, or wells, on the survey line will be the best way to ground-truth the survey data and enable a good interpretation of the model that is presented within this study.

8.1.2.3 Seismic Refraction and Reflection

A seismic survey was carried out running west to east for 1.5 km from the east side of the Mary Range. The data have been used to create a seismic refraction model. There was a good velocity contrast between layers enabling a good delineation of subsurface features. The seismic refraction model indicates that buried channels of reworked glacial outwash gravels are present in the shallow subsurface. The results indicate that seismic surveys are useful for determining lithological boundaries and areas where groundwater may be present.

The seismic section from the reflection data shows a strong reflector at a depth of approximately 175 m to 200 m and is interpreted to the top of the Glentanner Formation. The reflector is at a similar depth to the lower resistivity layer indicated by the TEM survey. This suggests that TEM can be used as an easier, reliable alternative to further define the hydrogeological basement throughout the Mackenzie Basin.

8.1.3 Hydrogeochemistry

During the course of this study 21 water samples were collected for chemistry analysis. The predominant water type within the Mackenzie Basin is Ca-Na-HCO_3, with Ca as the dominant cation and HCO_3 is the dominant anion. Three of the samples were collected from each of the glacial lakes for comparison with groundwater samples. The lakes have their own distinctive water chemistry. Results from some of the wells sampled were irregular (for example I37/0009) and these should be re-sampled to confirm the water chemistry.

The results were compared in terms of sub-basins and indicate that the groundwater flows within the Tekapo sub-basin are slower moving than those found in the Twizel sub-basin. The samples were also analysed for nitrate nitrogen and the results indicate that nitrate nitrogen is currently very low. These baseline results will be useful for comparison with future water samples to determine any affects of changing farming practices.

Analyses were also carried out for the presence of the heavy metal arsenic and the results indicate that one well has a level higher of arsenic than the New Zealand Drinking Water Standards (2005) recommend. The sample from Lake Ohau and a well close to Lake Ruataniwha also had detectable levels, but were well below the recommended levels specified in the Drinking Water Standards. It is suggested that the source of the arsenic is from the leaching of arsenopyrite from the bedrock in the surrounding ranges.

Water samples were not collected from Lake Benmore or from the rivers and streams within the Mackenzie Basin. These should be collected in the future to make an overall analysis of the water chemistry and quality to further define the link of surface water and groundwater flowing through the area.

8.1.4 Recharge Sources and Groundwater Age

Twenty water samples were collected for oxygen-18 analysis to determine recharge sources. Nine water samples were also collected for age tracer concentration analysis. CFCs and SF_6 were analysed in all nine samples and Tritium was analysed in five of the nine samples.

8.1.4.1 Recharge Sources

The results from the oxygen-18 ranged from -9.56 to -12.48. These values are much more negative in comparison to samples collected during other studies within the Canterbury Plains area. The technique of using oxygen-18 to determine recharge sources works well within the Canterbury Plains where the values from rainfall recharge and river recharge sources are distinctively different. Within the Mackenzie Basin this is not the case and makes using this technique to determine recharge sources difficult. However, samples were only collected from the three glacial lakes for comparison and not from the rivers within the area making the determination of recharge source more difficult. Samples from the rivers should be collected in the future to enable the identification of recharge sources. Sampling on a quarterly basis from some wells may also provide information on seasonal variations of recharge sources.

The use of chloride and nitrate nitrogen levels to determine recharge sources has also been used with success in the Canterbury Plains. Again, this method is not practical within the Mackenzie Basin as the chloride levels are extremely low (< 4.2 mg/L) and the nitrate nitrogen levels are virtually non-existent.

8.1.4.2 Groundwater Age

Groundwater within the Mackenzie Basin ranges in age from 11 to 115 years. The results of the age dating tracer concentrations have been provided as a range of ages for each sample, therefore an exact age for each sample cannot be given. The age ranges suggested, however, indicate that the groundwater system is only slowly recharging as a result of the low permeability of glacial formations and low hydraulic conductivity due to isolated lenses and layers of groundwater. Younger groundwater age results from shallow wells indicate that there is a separate, shallow, unconfined water table flowing close to the surface and that this system is recharged more rapidly by downwards infiltration from streams and rivers, especially within the Twizel sub-basin.

It is suggested that re-sampling of the same wells, along with additional wells, in the future will help to constrain the ages of groundwater within the Mackenzie Basin. Using other modelling methods and water chemistry in conjunction with age dating tracer concentrations may also prove to be useful.

8.1.5 Surface Hydrology and Springs

8.1.5.1 Springs

During the course of this study 53 permanently flowing springs were identified throughout the Mackenzie Basin. The two primary types of springs were fracture and depression springs. The springs within the fractured bedrock supply a number of areas for domestic and stock water supply. The springs are evident at a particular elevation throughout all of the bedrock highs such as the Mary Range, Grays Hills, and Mt John. The springs were only located and described at this stage. Measurement of spring flows would be useful in the future to quantify the contribution of springs to the hydrogeological system and could be used in future water balance calculations. Also, collecting samples from both types of springs for chemistry and age dating tracer analysis would be of interest. Determining the age of the spring water moving through the bedrock fractures would be useful for estimating the rate of recharge of these springs.

8.1.5.2 Surface Hydrology

Concurrent flow gaugings were undertaken by Environment Canterbury staff at 22 sites on a monthly basis to evaluate the seasonal patterns of river flows and to determine any interaction of surface water and groundwater that may be occurring. However, flow gaugings did not commence until October 2007, and so only five months of data was used in conjunction with groundwater level monitoring data. It is difficult to determine if there is a response of groundwater levels to surface water flows with a small number of gaugings. The concurrent gaugings can be used to indicate losing and gaining reaches, however, and this has been done for several sites within the study area. The two main rivers that appear to contribute an extensive amount of water to the groundwater system are Irishman Creek and Grays River, both within the Tekapo sub-basin. The Twizel River both gains and looses water to the groundwater system.

8.1.6 Hydrogeology

8.1.6.1 Specific Capacity and Transmissivity

Specific capacity values have been used to calculate transmissivity using the Bal (1996) equation. Although this equation was designed for use on the Canterbury Plains, it does provide an indication of transmissivity values in the absence of this data from pump tests. The values were plotted with regard to well depth and geographical location. There is an indication that shallow wells have a higher transmissivity, but this should be confirmed by conducting pump tests with time periods greater than several hours. The spatial trend of the values indicates that the most transmissive aquifers are within or close to the active riverbeds and alluvial fans. The lowest values are found in deeper wells away from streams and rivers and those wells close to or within moraine areas.

8.1.6.2 Groundwater Flow Direction

Piezometric surveys were conducted in both February and September 2007 to define the groundwater flow direction. Based on a limited amount of information, the general flow direction within the Twizel sub-basin is from the northwest towards Lake Benmore in the southeast. Within the Tekapo sub-basin the flow direction is from the northeast towards the Mary Range in the southwest.

8.1.6.3 Groundwater Fluctuations

Groundwater levels measured on a monthly basis, and levels measured every 15 minutes by water level loggers, indicate that in the wells close to or within the active riverbed areas fluctuate in response to rainfall and river flows. A response to rainfall events is also seen in wells close to the foothills of the Rollesby Range in the east of the Mackenzie Basin. All other wells have no detected response to rainfall or river flows. This indicates that the low permeability of the glacial lithologies does not allow rapid horizontal or vertical hydraulic conductivity to occur. The barometric pressure was also recorded within the Mackenzie Basin and no reaction to changes in pressure has been observed in the wells. If the deeper groundwater was fully confined a reaction to pressure changes would be seen. This suggests that the deeper groundwater is likely to be semi confined. The only seasonal variations were observed in wells close to the foothills suggesting that these wells are directly recharged by rainfall.

8.1.6.4 Groundwater Occurrence

Based on both previous reports and data collected during this study, it is suggested that there are three types of groundwater regimes present within the Mackenzie Basin. The higher permeability values of the Mt John Outwash Gravels (when compared with the underlying glacial formations) suggest that groundwater is likely to flow preferentially through this formation. The lenses and layers of openwork gravels provide groundwater flow paths. However, whether these flow paths are continuous and interconnected remains in doubt. The occurrence of the lenses and layers within the Mt John Outwash Gravels is likely to be highly variable both laterally and vertically due to the complex reworking of the gravels from the subsequent glacial advance.

A shallow groundwater table within the Post Glacial Alluvial Gravels in both sub-basins provides a considerable amount of water for both farming and domestic use. The shallow system is recharged from direct rainfall at the head of the catchment of local rivers and streams as wells as direct rainfall infiltration. The groundwater moves rapidly through the shallow subsurface and out to Lake Benmore in the south. The rapid flow of the groundwater means that there is unlikely to be adequate time for the shallow groundwater system to recharge the deeper groundwater system.

The large alluvial fans, especially the major fans in the east of the Mackenzie Basin, provide an area for direct rainfall infiltration and rainfall at the top of the ranges to move downwards in the direction of the Tekapo River to the west. The shallow groundwater system provides an extensive amount of water for stock and creates fertile ground, negating the need for irrigation in these areas.

A water balance was attempted as part of this study, but due to many unknown factors it is difficult to clearly quantify the recharge and storage capacity of the Mackenize Basin. Further investigations and data collection are required to accurately determine the groundwater resource available at depth.

8.2 RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

8.2.1 Future Investigations and Monitoring

Summarised below are the recommendations for future investigations to further define the hydrogeological system and to determine the most appropriate course of action for groundwater resource management.

- Monitoring wells should be drilled and logged in detail. Pump tests and water samples could be taken to provide baseline data for comparison to future data. Installing a well in the area to the east of the Tekapo River, close to the Grays River, could be used to determine recharge sources and transmissivity values in this area. Also, installing a well to the west of the Pukaki River could be used for similar purposes.

- Determine the hydraulic connectivity at depth by conducting pump tests over a three to four day period at different locations (for example at I38/0012 and H38/0035).

- Further investigation into the horizontal permeability is required to fully understand the recharge system. For example, using geophysics to the north of the Tekapo canal or within the pro-glacial lake, east of the Mary Range, may help to define whether groundwater is able to flow from the area in the north, where rainfall and surface water flows are higher, to the southern area of the Mackenzie Basin. Collecting groundwater and surface water samples from sites north of the Irishman Creek Fault and the moraine areas (for example, from Braemar Station) could be used to compare with water chemistry from sites south of these areas. If they are dissimilar it could indicate that these are not hydraulically linked.

- Installation of a lysimeter would enable the rainfall chemistry within the Mackenzie Basin to be measured and also to enable monitoring of seasonal changes of oxygen-18 values, chloride, and nitrate nitrogen levels. The data could then be compared to groundwater chemistry for recharge source evaluation.

- The lysimeter could also be used to determine the rate of infiltration of rainfall and the permeability of the soil surface. During the summer it was observed that large rainfall events occurred over very short time periods and the rainfall appeared to remain on the surface. Determining whether rainfall does not infiltrate the soil or whether a shallow layer is present that became fully saturated quickly would be useful to further the understanding of the system.

- Define actual evaporation rates for the Mackenzie Basin by collecting data from Aquaflex readings from farmer's irrigation systems. By defining the evapotranspiration rates within the Mackenzie Basin rather than using data from Tara Hills in the south will provide data for more accurate water balance calculations.

- Re-sample wells that have unusual chemistry results, for example I37/0009 where the pH was very high and I38/0004 where Na was predominant.

- Determine why the chemistry and yield of I38/0012 and I38/0014 are markedly different, yet the groundwater age and geology of the two wells are similar.

- Re-sample wells for age dating tracer concentrations and include other wells such as I38/0004. This well had an unusually high Na level and therefore may have quite an old groundwater age. Sampling H38/0035 could also be used to determine the rate at which (if at all) shallow water infiltrates downwards.

- Chemistry and oxygen-18 samples should be collected from Lake Benmore and rivers and streams within the Mackenzie Basin. Chemistry from Lake Benmore could be compared with water samples from the northern area of the Mackenzie Basin to determine if farming practices have any impact on water quality, and specifically to see if nitrate nitrogen levels increase as groundwater and surface water moves through the system from the northeast and northwest to the south. Collecting oxygen-18 samples from the rivers can be used to further define recharge sources of the groundwater system.

- Monitoring of water quality is required as farming intensifies to determine if there is any impact on groundwater resources. It may be possible that the rapid rate at which shallow water moves through the system enables the area to be 'flushed out' and that shallow groundwater quality remains fairly high. It may also be possible that the slow infiltration rate of recharge water for the deeper groundwater means that any water pollutants may be removed by sediments before reaching the deep groundwater system.

- Completion of the spring mapping and measuring the flow rates on springs, where possible, would provide information for water balance calculations. Collecting water samples would also provide comparative information for recharge source determination.

- Conduct further seismic surveys to investigate the presence of buried channels and to determine if they are continuous and connected. Also, conducting geophysical surveys within the Twizel sub-basin (similar to those done within the Tekapo sub-basin during this study) would further define the subsurface structure of the Mackenzie Basin.

- Continue water level monitoring to create a long term record. Twelve months of water level data is insufficient to determine if there are any seasonal trends or to determine whether increasing groundwater abstractions are impacting on groundwater resources.

- A review of the wells monitored during this study is contained in Table 8.1 along with recommendations for wells that could be monitored in the future.

8.2.2 Summary

The Mackenzie Basin contains a complex glacial structure within the subsurface which creates a complex groundwater system. Generally, the permeability of the glacial outwash gravels is low due to the high silt and clay content. The level of permeability not only varies between the glacial formations, but within each formation as well. Groundwater acts independently from river flows and rainfall apart from areas within active river beds or in the areas close to the foothills. Although the Mackenzie Basin has the appearance of being fairly arid, there is a substantial amount of surface water present in the form of springs and streams.

The overall chemistry of the groundwater for the Mackenzie Basin is similar, but there is an indication that the groundwater within the Tekapo sub-basin is slower moving compared to the Twizel sub-basin. The Twizel sub-basin is related to younger, faster moving, surface water recharge sources. The age of the groundwater ranges from 11 to 115 years old and generally the deep groundwater is older.

To better define the groundwater system, water level monitoring and river gaugings should be continued to create a long term record. Further chemistry and isotope samples should be collected. Pump tests should be undertaken to further define the transmissivity and permeability of the glacial deposits present within the Mackenzie Basin.

From the data collected during this study there is an indication that the recharge of the groundwater at depth is slow and that increased abstraction rates may quickly diminish the present quantity of the deep groundwater. Only monitoring and further investigations will help to manage and protect the groundwater resources within the Mackenzie Basin for the future.

Table 8.1: Summary of wells monitored during this study and recommendations for future monitoring.

Well Number	Highest Water Level	Lowest Water Level	Average Water Level	Accessibility	Pump Installed?	Reaction to Rivers or Rain?	Chemistry/ Age Analysis Done?	Recommend Continuation of Monitoring?
H38/0004	-3.20	-5.35	-4.07	Good	Y	Slight	N	N
H38/0010	-22.15	-22.50	-22.32	Good	N	No	N	Y
H38/0012	-1.05	-1.20	-1.12	Good	Y	Yes	N	N
H38/0013	-19.20	-20.30	-19.78	Good	N	Slight	N	Y
H38/0016	-26.90	-27.20	-27.04	Good	N	No	N	Y
H38/0021	-1.90	-2.60	-2.14	Good	Y	Yes	Y	Y
H38/0022	-1.30	-1.80	-1.56	Good	Y	Yes	N	N
H38/0025	-2.20	-2.50	-2.37	Good	Y	Yes	Y	N
H38/0030	-2.55	-3.00	-2.85	Good	Y	Yes	N	Y
H38/0032	-1.75	-2.15	-2.00	Moderate	N	Yes	N	Y
H38/0033	-1.60	-1.75	-1.69	Poor	N	Yes	N	N
H38/0038	-22.00	-24.50	-22.93	Good	Y	?	Y	Y
H38/0044	-22.90	-32.05	-30.87	Good	Y	No	N	N
H38/0045	-39.60	-39.70	-39.63	Good	Y	No	N	N
H38/0047	-32.70	-33.75	-33.94	Good	Y	No	N	Y
H38/0057	-44.20	-46.00	-45.22	Good	Y	Slight	Y	Y
H38/0058	-67.05	-70.20	-68.84	Good	N	Slight	N	Y
H38/0059	-10.05	-10.70	-10.36	Good	N	Slight	Y (+ Age = >95 yrs)	Y
H38/0063	-14.15	-23.20	-17.26	Good	Y	?	Y (+ Age = >93 yrs)	N
H38/0074	-8.40	-8.70	-8.59	Moderate	N	Slight	N	N
H38/0118	-2.20	Dry	-2.45	Good	N	Slight	N	N
H38/0119	-1.75	-2.30	-2.12	Good	N	Slight	N	N
H38/0120	-1.55	Dry	-1.53	Good	N	Slight	N	N
H38/0140	-3.60	-3.85	-3.71	Good	N	Slight	N	N
H38/0188	-5.65	-7.20	-6.55	Good	Y	Slight	Y	N
I37/0013	0.99	0.94	0.96	Good	Y	?	Y (+ Age = 23-54 yrs)	Y
I37/0029	-20.25	-20.45	-20.37	Poor	N	No	N	N
I37/0031	-35.10	-35.30	-35.23	Poor	N	No	N	N
I37/0032	-33.65	Dry	-33.65	Poor	N	No	N	N
I38/0003	-5.70	-8.10	-6.80	Good	N	Yes	Y	Y
I38/0004	-0.60	-1.40	-1.13	Good	N	Yes	Y	Y
I38/0012	-33.80	-34.90	-34.50	Good	N	No	N	N
I38/0014	-3.84	-5.35	-4.65	Good	Y	No	Y (+ Age = >100 yrs)	Y
I38/0015	-10.35	-11.65	-11.02	Good	N	No	Y (+ Age = 92-115 yrs)	Y
I38/0045	-4.00	Dry	-4.09	Moderate	N	Slight	N	N
I38/0049	-14.80	-15.95	-15.52	Poor	N	Slight	N	N
I38/0050	-13.50	-16.45	-15.18	Poor	N	Slight	N	Y
I38/0052	-0.55	-1.70	-1.03	Good	Y	Yes	Y (+ Age = ?)	Y
I38/0053	-1.30	-4.95	-3.16	Good	Y	Yes	Y	N
I39/0004	-4.95	-6.00	-5.71	Good	N	No	Y (+ Age = 80-82 yrs)	N
I39/0005	-4.80	-5.20	-4.99	Good	N	No	N	Y
I39/0007	-1.25	-3.25	-1.87	Good	Y	No	Y (+ Age = 11-42 yrs)	Y
#2	-3.28	-3.70	-3.60	Moderate	N	No	N	N
#3	-5.00	Dry	-5.11	Moderate	N	No	N	N

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Hydrogeology

of the

Mackenzie Basin

Volume Two: Appendices

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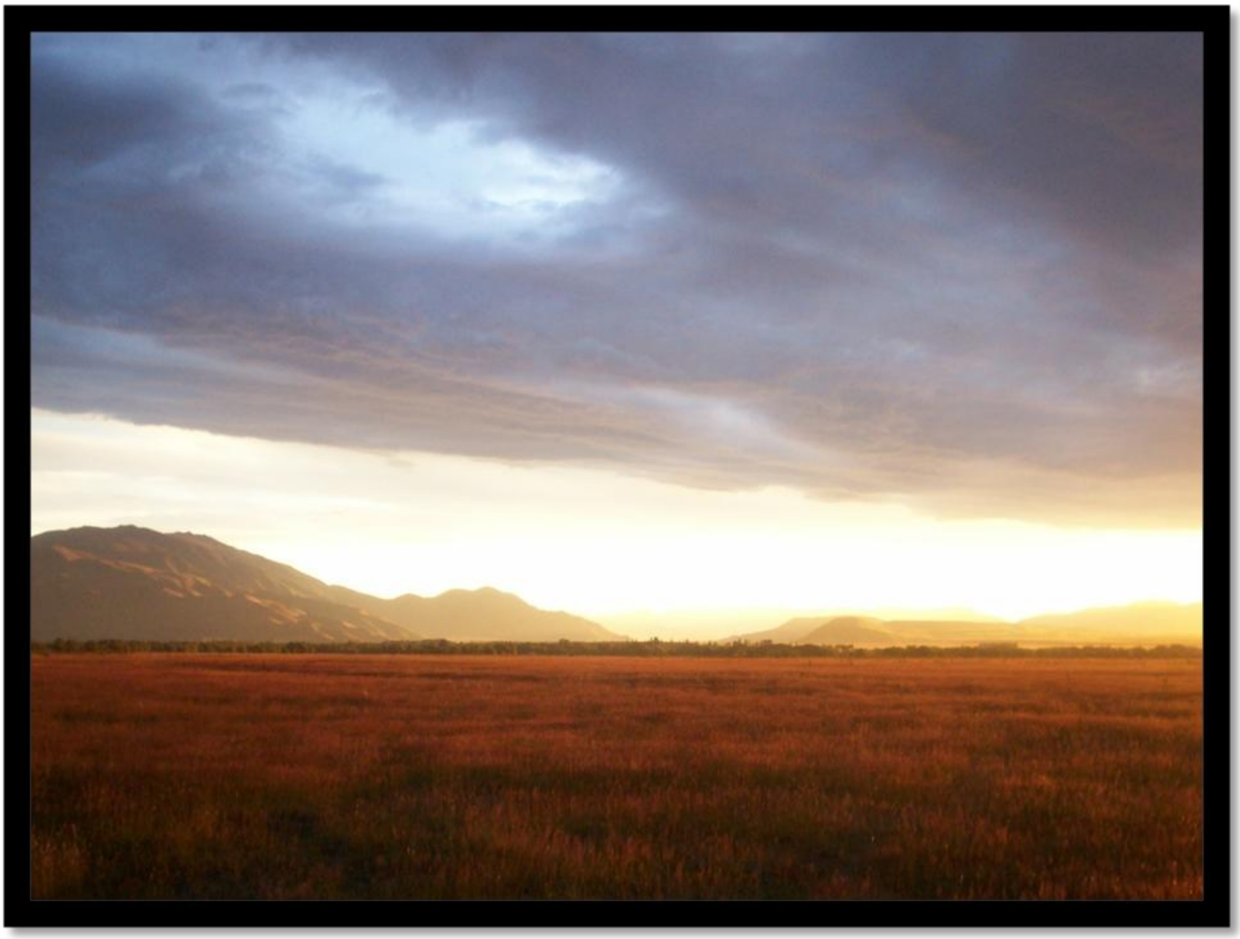

The Mackenzie Basin

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Appendix 1A

Rainfall Data

(see attached CD)

Appendix 2A

Detailed Stratigraphy

1.1 REGIONAL GEOLOGY

The basement of the Mackenzie Basin is formed by the Torlesse Supergroup which contains three major belts of rocks; the Rakaia and Pahau subterranes and the Esk Head Melange. During the Late Carboniferous to Triassic the Rakaia terrane sediments, which were derived from the erosion of Gondwana rocks, were tectonically stacked and imbricated during accretion on to the proto-Pacific margin of Gondwana (Cox & Barrell, 2007). During the Jurassic the Rakaia subterrane was folded and amalgamated with the Caples subterrane (Bradshaw, 1989). The Rakaia subterrane was also subjected to a regional, low grade, prehnite-pumpellyite facies metamorphism with parts of the Rakaia subterrane being altered to semi-schist and schist (Cox & Barrell, 2007). The Rakaia subterrane grades laterally in the southwest of the region into the Haast Schist (Field & Browne, 1989).

During the Late Cretaceous the Waipounamu erosion surface was formed, creating a region of mild relief and in places represents a break in the stratigraphic record of 20 million years (LeMasurier & Landis, 1996). Within the Canterbury Plains and inland basins, the Waipounamu erosion surface is either buried beneath younger sediments or has been entirely removed by Neogene uplift and erosion. Regional subsidence led to the start of sedimentation of the Eyre Group in the east, with only the western parts of the Canterbury region being above sea level by the Oligocene (Cox & Barrell, 2007).

During the mid Oligocene the Marshall Paraconformity created a surface of primarily non-deposition, but also erosion, as a result of glacioeustatic fall and related oceanographic processes combined with a fall in base level. This surface represents a break in sedimentation of 2 to 4 Ma at approximately 32 to 29 Ma (Fulthorpe *et al*, 1996; Cox & Barrell, 2007). From the Late Oligocene to earliest Miocene the Kekenodon Group were deposited slowly in most of the region, however they are missing in the far west of Canterbury where younger sediments lie unconformably on Rakaia terrane (Cox & Barrell, 2007).

By the early Miocene the Australian-Pacific plate boundary formed and the Neogene Alpine Fault came into existence (Sutherland *et al.*, 2000) (Figure 1.1). The new plate boundary created uplift to the east of the Alpine Fault and subsidence further to the east causing the deposition of an eastward-prograding wedge of sediment, the Motunau Group. In the Early to Middle Miocene the White Rock Coal Measures were laid down. Within the Mackenzie Basin area the White Rock Coal Measures lie directly on the leached Rakaia Terrane. During the Late Miocene the Southern Alps continued to grow upwards and, combined with erosion, provided the greywacke and schist sourced sediments that accumulate across the region during the Pliocene and Quaternary (Cox &

Barrell, 2007). During the Kaikoura Orogeny, faulting and folding formed the Canterbury basins and ranges (Suggate, 1973). During this period the down warping formed a tectonic depression which is now the location of the Mackenzie Basin (MacFarlane, 1981). In the Late Miocene to Early Quaternary the Kowai Formation, locally known as the Glentanner Formation, was deposited. Following a period of erosion, the Quaternary entailed a series of glacial and interglacial periods, and within the Mackenzie Basin this is represented by four major ice advances.

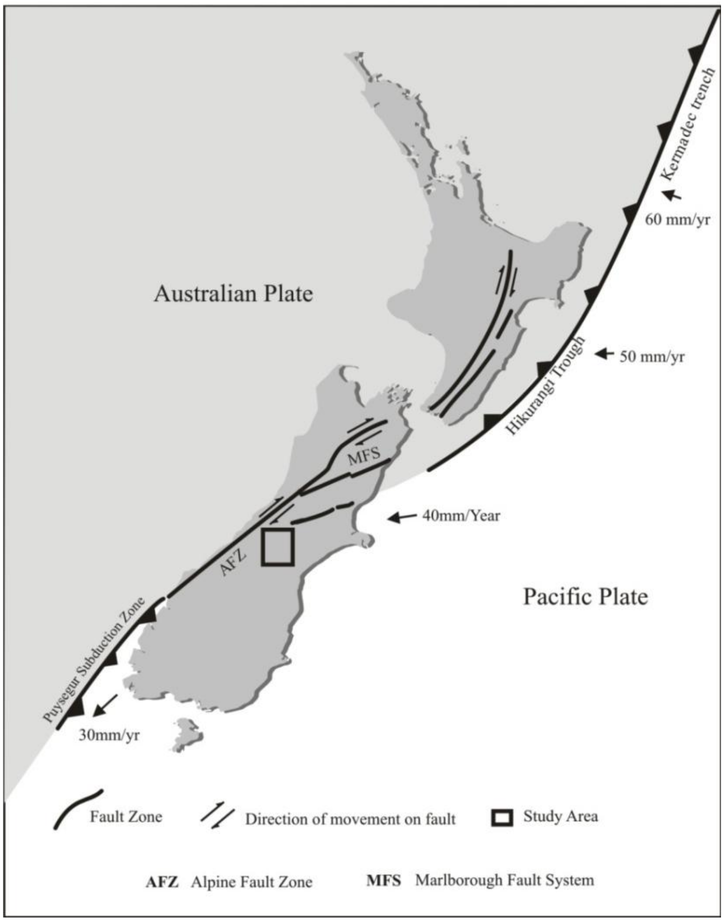


Figure 1.1: New Zealand tectonic plate boundary (modified from Finnemore, 2004)

1.1 BASEMENT ROCKS (G)

The Basement consists of Torlesse Supergroup and Haast Schist derivatives. The bedrock can be seen in outcrops on all the ranges surrounding the Mackenzie Basin and within the inliers such as the Mary Range. The Torlesse Terrane is predominantly a very well indurated, unweathered, greywacke. The grey sandstone (arenite) is interbedded with dark grey siltstone and mudstone (argillite) (Figure 1.2). The sandstone consists of quartz, plagioclase, K-feldspar, muscovite and minor rock fragments (Sporli & Lillie, 1972). Generally the bedrock is of a low metamorphic grade (prehnite-pumpellyite facies) with prehnite occurring as the main metamorphic mineral (Fox, 1987). In the central belt of the Ben Ohau Range in the west, low grade schist has developed (Sporli & Lillie, 1972). The upper part of the bedrock is weathered, jointed, and fractured (Figure

1.3). Highly weathered, weak sandstone lumps and fernlike staining on joint surfaces are indicative of chemical weathering as water penetrates along bedding surfaces (Macfarlane, 1995). Weathering penetration along bedding planes was observed by light brownish discolouration with a yellow clay film in drill cores at depths up to 60 m below the surface.

1.2 TERTIARY SEDIMENTARY DEPOSITS

1.2.1 Eyre Group (eg)

In the Mackenzie Basin the Eyre Group outcrops in a small localised area in the Hakataramea Pass on the eastern side of the Basin. The presence of this formation at depth within the basin is inferred by strong reflections seen during a large scale crustal transect seismic survey, SIGHT98, and a gravity survey that crossed the Irishman Creek Fault (S Cox pers. comm., 2008). The presence of a mud volcano in the hanging wall of the Irishman Creek Fault is also thought to possibly indicate the presence of limestone at depth; the mud volcano indicates overpressure at depth, and the green, red, and white rivulets in the mud are possibly from carbonate sediment such as limestone (Chetwin, 1998) (Figure 1.4). Mansergh (1973) also notes that during the Tertiary a marine transgression reached the southern and eastern limits of the Mackenzie Basin leaving remnants of marine and non-marine beds in the passes leading into the Basin. In the northern slopes of the Hakataramea Pass, exposures of white, green and brown sands with shell fragments were observed by Speight (1940) who notes that they represent the sole example of marine beds within the Basin. The same marine beds were also observed by Speight (1961) in the extreme south east of the Basin. The formation within the marine sedimentary Eyre Group that has been mapped by Cox & Barrell (2007) includes pale grey silty quartz sandstone and olive-grey fine sandy siltstone or mudstone. Muddy limestone or very calcareous mudstone is common at the top of the formation.

1.2.2 White Rock Coal Measures (wrc)

Although no known outcrops of the White Rock Coal Measures can be seen within the Basin their presence is mentioned by Gair (1967). Locally, the unit is thought to overlie the Torlesse Terrane as no lower Tertiary formations are known (Gair, 1978). However, Chetwin (1998) suggests that an Oligocene limestone, similar to the nearby Cannington Basin, is present at approximately a 1.7 km depth, below the White Rock Coal Measures, based on seismic reflection data. The presence of this Tertiary unit can only be inferred from work in other areas (Cannington Basin to the east), and from seismic reflections as there are no outcrops of this unit at the surface within the Mackenzie Basin.

The White Rock Coal Measures are described as a weak claystone, siltstone and sandstone with minor conglomerate and thin non-quartzose coal seams formed during the regression of the sea

(Gair, 1967; Cox & Barrell, 2007). Within the neighbouring Cannington Basin to the east the lignite seams within the White Rock Coal Measures are over a metre thick and contain veins of gypsum along the bedding planes (Gair, 1958).

1.2.3 Kowai Formation (Glentanner Formation) (gt)

Overlying the White Rock Coal Measures or the Torlesse Terrane, and separated by an angular unconformity, is the Kowai Formation, locally known as the Glentanner Formation. The formation was tilted and faulted during the Kaikoura Orogeny (Gair, 1967). The non-marine, sub-angular, blue brown-weathered greywacke conglomerate is interbedded with very compact sand, silts, and silty clays (Gair, 1967; Macfarlane, 1981; Fox, 1987; Cox & Barrell, 2007). Organic material is often found within the blue-grey silt and silty clay beds contained within the Glentanner Formation (Figure 1.5). The formation is also relatively impermeable in situ (Macfarlane, 1981).

Within the Lake Pukaki area the Glentanner Formation is described as a tectonically deformed gravel sequence with rare fossiliferous, fine grained horizons and pollen (Mildenhall, 2001). A Pliocene age has been suggested for the formation based on fossil pollen located within the Lake Pukaki area (Mildenhall, 2001). During the early phases of deposition, the Glentanner Formation was deposited at a time when a beech forest was present in a warm and wet environment, indicating an interglacial period (Mansergh, 1973; Mildenhall, 2001). Further evidence for this time period and climate is also seen in the outcrop at the Irishman Creek Fault where wood samples can be found within the Formation. Dating of a wood sample was attempted, but unsuccessful (Fox, 1987). However, the wood sample is considered to be from a type of conifer (Podocarpus affinity) indicating a warm climate (Fox, 1987) similar to the environment in which the fossil pollen samples were deposited. Near the top of the Glentanner Formation sequence there is evidence of the start of a glacial period as forest vegetation disappears and is replaced by grassland/scrubland vegetation (Mildenhall, 2001).

The Glentanner Formation outcrops in small pockets throughout the Basin and can be seen within the study area at the Irishman Creek Fault, within the Ostler Fault Zone, and on the western side of Lake Pukaki. The formation is exposed on Glen Lyon Road due to the uplift of the Ruataniwha Fault, where it dips between 25 and 50 degrees to the west (Macfarlane, 1981). The formation is exposed in the Irishman Creek Gorge due to uplift by the Irishman Creek Fault, where it dips 60 degrees to the southeast (Chetwin, 1998).

1.3 QUATERNARY DEPOSITS

Within the Mackenzie Basin there are four major glacial advances, three during the Otiran (Tekapo, Mt John, and Balmoral) and one within the Waimean or Waimaunga (Wolds) (Gair, 1967; Oborn, 1978; Cox & Barrell, 2007). A younger, minor advance is known as Birch Hill; however this advance is not present within the study area. The suggested extent of each ice advance is illustrated in Figure 1. . The formations are listed in comparison to other glacial advances in the surrounding area (Table 1.1). The ages for each formation have been researched by a number of sources over the years and the estimated age ranges from these are listed in Table 1.2. Further discussion on the ages of the formations that are not included in Table 2.2 can be found in McGregor (1963); Suggate & Moar (1970); Moar & Suggate (1973); Porter (1975); Tuck (1975); Webb (1976); Wellman (1979); Liedtke (1981); Maizels (1989); Schaefer *et al.* (2001); and Schaefer *et al.* (2006), amongst others.

The glacial tills are composed of predominantly greywacke along with schist and argillite. The glacial outwash gravels are predominantly greywacke gravels with sand and silts. The older formations tend to be less permeable than younger formations due to compaction at depth. However, Oborn (1978) notes that the permeability range over all formations is likely to be little greater than the range of permeability within one formation. The glacial deposits are overlain by post glacial Holocene alluvial deposits.

1.3.1 Wolds Formation (wo)

The Wolds Formation is described by Read (1976) and Macfarlane (1981) as a brown, moderately and highly weathered sandy gravel, with poorly developed bedding. Rare, discontinuous thin lenses of openwork gravel, silt, or sand can be found. Voids between the clasts are all filled with a brown silt or yellow silty clay matrix. The Wolds Formation rests unconformably on the Glentanner Formation.

1.3.2 Interglacial Unit (I)

In the Twizel sub-basin a narrow band of light grey, yellow fine sandy silt, with minor fine gravel is defined as an interglacial unit (Read, 1976). At the Ostler Fault section, close to the Fraser Stream in Twizel, the Interglacial Unit unconformably overlies both the Glentanner and Wolds Formations in a bed up to 2.5 m thick. The unit thickens to the west with up to 4 m of weathered gravel and plastic silty clay infilling voids under the silt band (Macfarlane, 1981). The unit is thought to be from material eroded from the uplifted Glentanner and Wolds Formations in the Ostler Fault section, and has been re-deposited as a wedge shaped deposit during the warm interglacial period (Read, 1976). The interglacial unit is conformably overlain by the Balmoral Outwash Gravels (Macfarlane, 1981).

Figure 1.2: Interbedded sandstone and argillite of the Torlesse Terrane. View to the east
(Grid ref: 2284995 5718878).

Figure 1.3: Fractured bedrock outcrop in Edward Stream. (Grid ref: 2315120 5687042).

Figure 1.4: A mud volcano at Irishman Creek Fault, observed in 1998 during a geophysical survey. View looking north west (photo: Chetwin, 1998).

Figure 1.5: Organic material in the Glentanner Formation at Irishman Creek Gorge. Lignite beds with sulphur staining present also. View to the west
(Grid ref: 2295670 5684957).

A: View to west (Grid ref: 2295670 5684957)

B: View to west (Grid ref: 2274753 5660583)

C: View to west (Grid ref: 2277737 5696633)

D: (Grid ref: 2274753 5660583)

Figure 1.6: Glentanner Formation outcrops in various places within the Mackenzie Basin including: A) Irishman Creek Fault Gorge; B) Ostler Fault on Glen Lyon Road; C) Behind Glentanner Station on the west side of Lake Pukaki; D) Close up view of the formation within the Ostler Fault outcrop.

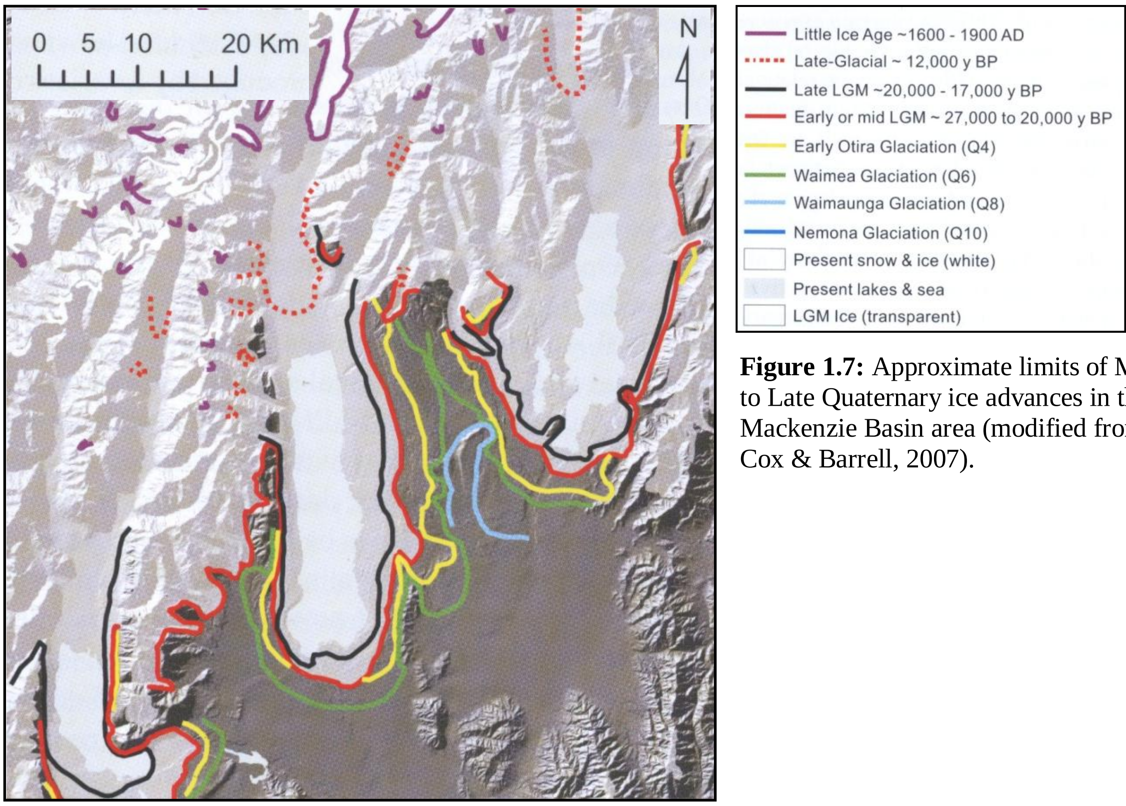


Figure 1.7: Approximate limits of Mid to Late Quaternary ice advances in the Mackenzie Basin area (modified from Cox & Barrell, 2007).

Table 1.1: Correlation of glacial formations with other areas covered by the Aoraki QMap (modified from Cox & Barrell, 2007).

Mackenzie Basin	Aoraki QMap Area	Central Canterbury	Upper Rangitata, South Ashburton
Gair (1967) Maizels (1989)	Cox & Barrell (2007)	Gregg (1964) Gair (1967) Suggate (1973) Oliver & Keene (1989)	Mabin (1980) Oliver & Keene (1989, 1990)
Post-glacial	Q1t, Q1a	Post-glacial	-
Birch Hill	Q1t, Q1a	-	Two Thumbs (part)
Tekapo Mt John	Q2t, Q2a	St Bernard Burnham Windwhistle (part)	Two Thumbs (part) Spider Lakes Hakatere Trinity
Balmoral	Q4t, Q4a Q6t, Q6a	Windwhistle (part) Woodlands	Dogs Hill
Wolds	mQt Q8t, Q8a Q10t, Q10a	Hororata	Pyramid

Table 1.2: Comparison of suggested ages from different sources of the various glacial formations present within the Mackenzie Basin. The shaded areas represent interglacial periods (modified from Maizels, 1989; Lapwood, 2006).

<table>
<tr><th rowspan="2">Formation</th><th colspan="2">Cox & Barrell (2007)</th><th colspan="3">Amos et al. (2007)</th><th colspan="3">Barrell and Cox (2003)</th><th>Blick et al., (1989)</th><th>Fox (1987)</th><th>McGregor (1981)</th><th>Mansergh (1973)</th><th>Gair (1967)</th><th>Speight (1961)</th></tr>
<tr><th>OIS Age</th><th>Age</th><th>Climatic Event</th><th>MIS Stage</th><th>Age (technique)</th><th>Climatic Event</th><th>MIS Stage</th><th>Age (technique)</th><th>Age (Years BP)</th><th>Age (Years BP)</th><th>Age (Years BP)</th><th>Age (technique)</th><th>Age (Years BP)</th><th>Age (Years BP)</th></tr>
<tr><td>(Holocene till/outwash)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>‘Neoglacial’</td><td>1</td><td>0 to 5 ka (14C)</td><td>-</td><td>-</td><td>-</td><td>3.3 to 6 ka</td><td>-</td><td>-</td></tr>
<tr><td>Birch Hill</td><td>1?</td><td>Late glacial ~11 to 14 ka</td><td>-</td><td>-</td><td>-</td><td>Late glacial</td><td>1 - 2</td><td>10 to 12 ka (10Be)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>>5.12 ka ±140</td><td>-</td></tr>
<tr><td>Tekapo</td><td>2</td><td>~17.4 ka ±1 (Shaefer et al., 2006)</td><td>Otira Glaciation</td><td>2</td><td>12 to 18 ka</td><td>Late Otira Glaciation</td><td>2</td><td>16 to 18 ka (14C/10Be)</td><td>14 ka</td><td>14 to 16 ka</td><td>14 ka</td><td>14 ka</td><td>14 ka</td><td>- (Pukaki Surface)</td></tr>
<tr><td>Mt John</td><td>2</td><td>~17 to 27 ka</td><td>Otira Glaciation</td><td>2</td><td>18 to 24 ka</td><td>Late Otira Glaciation</td><td>2</td><td>18 to 24 ka (10Be)</td><td>16 to 17 ka</td><td>18 ka</td><td>18 to 16 ka</td><td>16 ka</td><td>17 to 22 ka</td><td>22.3 ka ±350 (Maryburn Surface)</td></tr>
<tr><td rowspan="2">Balmoral II</td><td rowspan="2">4</td><td rowspan="2">Early Otira Glaciation</td><td rowspan="2">Early Otira Glaciation</td><td rowspan="2">4</td><td rowspan="2">59 to 74 ka</td><td>? Early Otira Glaciation</td><td>? 4</td><td>59 to 71 ka</td><td rowspan="4">-</td><td rowspan="4">65 ka</td><td rowspan="4">51 ka</td><td rowspan="4">36.4 ka ±3,150 (14C) Minimum age</td><td rowspan="4">> 35 ka</td><td rowspan="4">51 ka (Irishman Surface)</td></tr>
<tr><td>Kaihinu Interglacial</td><td>5</td><td>-</td></tr>
<tr><td rowspan="2">Balmoral I</td><td rowspan="2">6</td><td rowspan="2">Waimea Glaciation</td><td rowspan="2">Kaihinu Interglacial</td><td rowspan="2">5</td><td rowspan="2">~80 to 90 ka</td><td>? Waimea Glaciation</td><td>? 6</td><td>128 to 186 ka</td></tr>
<tr><td>Karoro Interglacial</td><td>7</td><td>-</td></tr>
<tr><td rowspan="3">Wolds</td><td rowspan="3">8</td><td rowspan="3">Waimaunga Glaciation</td><td>Waimea Glaciation</td><td>6</td><td>130 to 190 ka</td><td rowspan="3">? Waimaunga Glaciation</td><td rowspan="3">? 8</td><td rowspan="3">245 to 303 ka Possible minimum age</td><td rowspan="3">-</td><td rowspan="3">150 ka</td><td rowspan="3">105 ka</td><td rowspan="3">-</td><td rowspan="3">> 100 ka</td><td rowspan="3">105 ka (Stevenson Surface)</td></tr>
<tr><td>Karoro Interglacial</td><td>7</td><td>-</td></tr>
<tr><td>Waimaunga Glaciation</td><td>8</td><td>244 to 297 ka</td></tr>
</table>

1.3.3 Balmoral Formation

During the glacial period (Waimea to Early Otira) it is thought the Balmoral Advance was subjected to two phases of advance and retreat. The two phases are represented by twin lateral benches on the Ohau and Mary Ranges. The Balmoral Moraine can be seen where the ice from the Lake Pukaki area has spilled into the Tekapo area around the northern end of the Mary Range (Mansergh, 1973).

1.3.3.1 Balmoral Till (bt)

The Balmoral till is yellow-brown, moderately weathered gravel with silts and clays present. Close to the terminal moraine the till can be seen as chaotic, with poor grading. Subangular to subrounded greywacke clasts are present with boulders ranging up to 4 m in diameter (Figure 1.8. and Figure 1.9).

1.3.3.2 Balmoral Outwash Gravels (bo)

The Balmoral Outwash Gravels are brown or yellow-brown, slightly or moderately weathered, sandy gravels (Figure 1.10 and Figure 1.11). Voids are infilled with silt and clay. Bedding is present and is based on sand lenses and rare thin layers of well sorted fine gravel dipping between horizontal and 15 degrees to the west (Read, 1976). Within several gravel pits on State Highway 8, the Balmoral Outwash Gravels can be seen to contain thin silt lenses also. In the Ostler Fault section, the Balmoral Outwash Gravels conformably overlie the Interglacial Unit, and there is a gently folded Balmoral surface present between Mt Ostler and the Fraser Stream (Read, 1976).

1.3.4 Mt John Formation

The extent of the Mt John Advance was not as extensive as the preceding Balmoral Advance. Near Lake Pukaki two phases of the Mt John Advance are evident to the southeast of the lake and to the north of the Mary Range where the ice has followed the path of the Balmoral Advance and spilled over into the Tekapo area (Mansergh, 1973).

1.3.4.1 Mt John Till (mjt)

The Mt John Till represents the moraine material associated with this glacial advance. The till is light grey to pale yellow, poorly sorted gravely sandy silt, with rare cobbles and boulders (up to 3 m) (Read, 1976; Macfarlane 1981). Lenses of sandy gravel with rare silt are occasionally found (Read, 1976). The clasts are either angular or sub-angular to sub-rounded unweathered greywacke which occasionally occur in bedded lenses (Macfarlane, 1981) (Figure 1.12).

In the Lake Pukaki outlet area (grid ref: 2282342 5664715), the Mt John Till was deposited as the ice retreated. The terminal moraines were subsequently mostly removed by melt water flowing from the ice front (Read, 1976).

Figure 1.8: Balmoral Till – location is approximately 500 m south of the Pukaki spillway. View is to the east (Grid ref: 2283104 5663018).

Figure 1.9: Balmoral Till overlain by Mt John Outwash Gravels. View is to the east (Grid ref: 2283104 5663018).

Figure 1.10: Balmoral Outwash Gravels. View is to the north (Grid ref: 2295096 5666000).

Figure 1.11: Balmoral Outwash Gravels overlain by Mt John Outwash Gravels. View is to the west (Grid ref: 2284980 5660167).

1.3.4.2 Mt John Outwash Gravels (mjo)

The Mount John Outwash Gravels are grey, well graded, and fine to coarse gravel with some sand and cobbles (Figure 1.13). Silt and clay lenses are present in some areas. The unweathered greywacke clasts are sub-angular to sub-rounded. Sub-horizontal bedding can be seen in outcrops of the formation and was also identified in shafts dug during the canal construction period. At depth, open, well sorted gravel layers, cross bedded infilled channels, and sand lenses are common (MacFarlane, 1981) (Figure 1.14 and Figure 1.15). Channel structures can also be seen in the section in the Pukaki River, where buried channel structures indicate paleo river flows from west to east (Figure 1.11). Generally the cobbles and boulders are found in relatively coarse layers near the top 20 to 30 m of the unit. Voids are filled with pale yellow silt and clay varying from 1-2% of silt and clay (virtually absent) to 7-8% of silt and clay (void filling) (Macfarlane, 1995). The interstitial silt and clay is highly plastic and commonly present at the base of openwork layers where accumulation has resulted from percolating groundwater (Macfarlane, 1995).

The Mt John Outwash gravels were deposited as an aggradational fan by the river ahead of the Mt John ice advance. In the present outlet of Lake Pukaki advancing ice gouged a deep hole in the Mt John Outwash Gravel and then over-rode the gravels to the south, west and east. The ice gouge hole was partially back filled with what Read (1976) describes as Ice Contact Gravels and Contorted Sediments Silt as the ice retreated towards the north. Within the area to the south of the Lake Pukaki outlet, the unit was observed to be over 100 m thick by Read (1976).

In the Ohau River area the Mt John Outwash Gravels are greater than 50 m thick. The gravels have been incised to depths of up to 40 m by the river leaving behind flights of terraces. Within the lower terraces area and around the Ruataniwha reservoir the Mt John Outwash Gravels are approximately 5 to 10 m thick (Macfarlane, 1995).

1.3.5 Tekapo Formation

The Tekapo Advance is considered to be a minor event that occurred soon after the retreat of the Mt John Advance (Mansergh, 1973). Within the Lake Pukaki area the Tekapo terminal moraine forms a single loop of till approximately 20 m thick which lies on its own outwash gravels and the Mt John Outwash Gravels in places (Mansergh, 1973).

1.3.5.1 Tekapo Till (tt)

The Tekapo Till is light yellow grey, fine to coarse gravels with silt, sand, and some cobbles. The unit has variable grading and distorted bedding in places (Figure 1.17 and Figure 1.16).

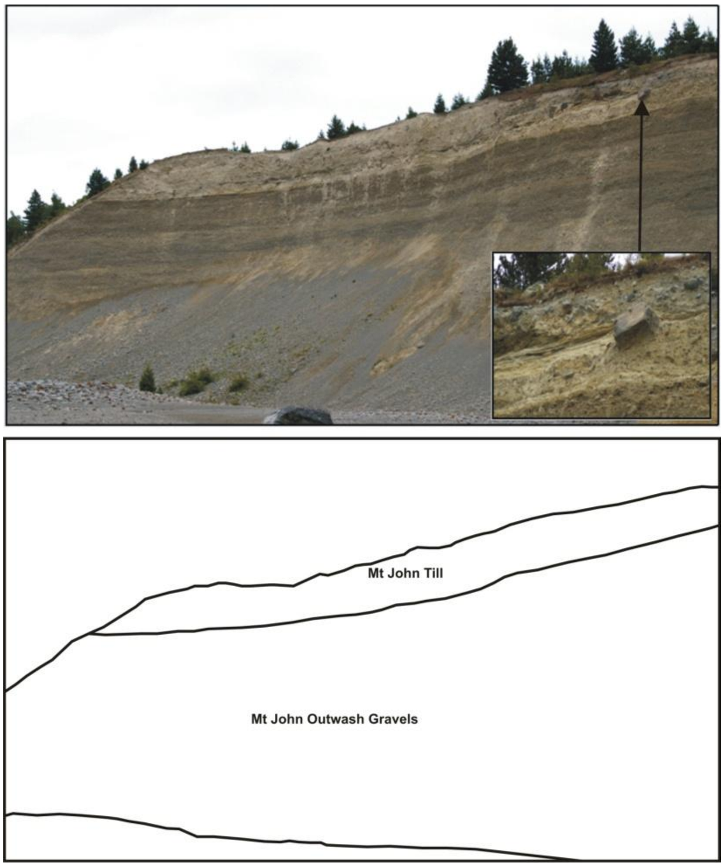


Figure 1.12: Mt John Till overlying the Mt John Outwash Gravels. Terrace is ~50 metres high. View looking north east. (Inset: close up of the Mt John Till) (Grid ref: 2283104 5663018).

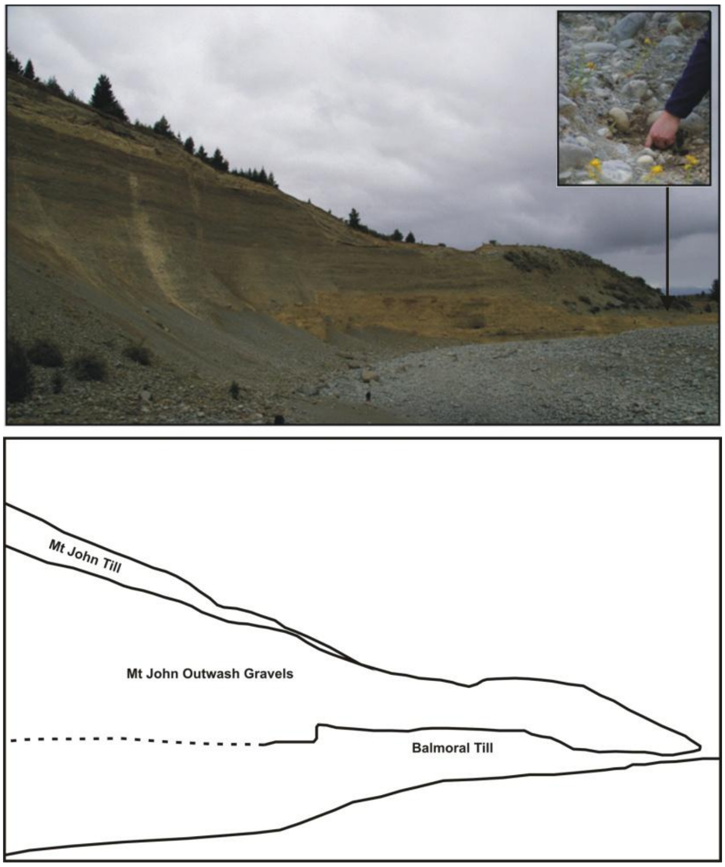


Figure 1.13: Mt John Outwash Gravels overlying the Balmoral Till. Person in forefront for scale (terrace ~50 m high). View looking south east. (Inset: close up of the Mt John Outwash Gravels) (Grid ref: 2283104 5663018)

Figure 1.14: Subhorizontal bedding with alternating coarse and fine layers within the Mt John Outwash Gravels (photo: Macfarlane, 1981).

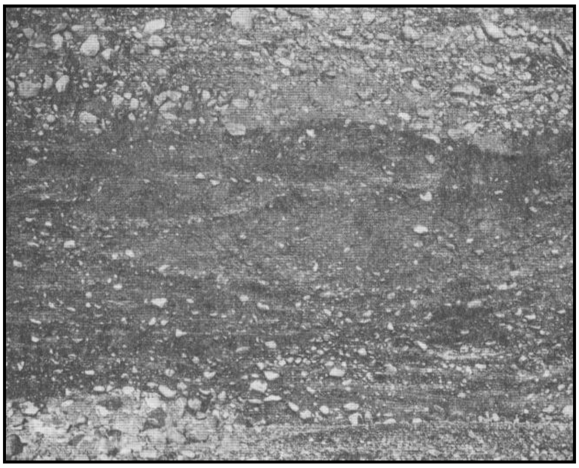


Figure 1.15: Infilled channel with cross bedding within the Mt John Outwash Gravels. The upper, cleaner, layer is the Tekapo Outwash Gravels (photo: Macfarlane, 1981).

Figure 1.16: Tekapo Till on the south west shore of Lake Tekapo. Layered lake sediments at left of picture. Person for scale. (Grid ref: 2309164 5692159).

Figure 1.17: Distorted and layered Tekapo Till on the west shore of Lake Pukaki. Scale is approximately 2 m across (Grid ref: 2280915 5665188).

Below the Tekapo Till is a narrow band (generally <2 m) of highly disturbed material which has been mapped during the canal construction period as a contact zone. The contact zone represents material which has been disturbed by the thrusting of the Tekapo Till over the underlying units (Macfarlane, 1981). The contact zone has been described by Read (1976) as a grey faintly bedded, fine to coarse gravel with some sand, rare boulders, and very rare or rare silt. Boulders form a large proportion of the material, but also include variations of open gravel, silt, silty sandy boulder gravel, pockets, lenses, or layers (Read, 1976).

1.3.5.2 Tekapo Outwash Gravels (to)

The Tekapo Outwash Gravels are generally grey, unweathered sandy greywacke gravels, with some cobbles and boulders, and rare silt, which range from well to poorly graded. The Tekapo Outwash Gravels form a thin surface veneer up to 5 m thick (Read, 1976; Macfarlane, 1995). The gravels are hard to differentiate from the Mt John Outwash Gravels; however the Tekapo Outwash Gravels do have consistently low silt and clay content and less variable grading in comparison to the Mt John Outwash Gravels (Read, 1976, Macfarlane, 1995). The Tekapo Outwash Gravels may be distinguished from other formations on outwash surfaces which are generally stony and have many well defined, abandoned, braided channels (Oborn, 1978).

1.3.6 Post Glacial Alluvial Gravels (pga)

The Post Glacial Alluvial Gravels consist of unweathered, sub-angular to sub-rounded greywacke sandy gravel, clean, well graded sandy coarse gravel with lenses of well sorted gravel and some sand lenses (Macfarlane, 1995). Traces of light yellow silt and silty clay are present in the voids (Read, 1976). It has been observed that the lower part of the unit has minor weathering and a high silt content within the voids in comparison to the upper part of the unit (Read, 1974). The Post Glacial Gravels are present as extensive aggradational fans between the Twizel River and the Fraser Stream (Macfarlane, 1981).

1.3.7 Fan Alluvium (fa)

The weathered greywacke bedrock provides extensive material for Fan Alluvium which forms as thick fan shaped wedges in gullies along the Ranges such as the Rollesby Range, the Mary Range, and the Ben Ohau Range. The two major fan surfaces that have been identified are on the eastern side of the Basin within the Mackenzie Pass and Hakataramere Pass.

Appendix 3A

Previous Work

Multiple geophysical surveys have been conducted over the past 60 years within the Mackenzie Basin. The purpose and technique of each survey has varied. Initially seismic refraction surveys were conducted to define the subsurface, and bedrock topography, for the purpose of canal construction. In 1969 MacDonald conducted resistivity soundings at the Pukaki High Dam site to determine any groundwater table present in the area. Seismic profiling and other subsurface investigations have also been used to provide detail on foundation conditions and to delineate geological boundaries for canal lining material (Macfarlane, 1981). It was also noted from seismic surveys that, in general, the older glacial formations have a higher seismic velocity than the younger formations (Oborn, 1978). Twelve seismic refraction lines were shot close to the Ruataniwha dam site to determine the topography of the bedrock. A good velocity contrast between the bedrock and overlying gravels was observed (Macfarlane, 1995).

Since the construction period ceased in 1985, the focus of interest has moved to geological structures. Predominantly large scale surveys undertaken to define the depth to basement within the basin and crustal structures relating to plate tectonics.

In 1983 the sedimentary environment of Lake Tekapo was investigated by Pickrill & Irwin (1983). Sediment cores were collected and seismic reflection survey lines were run E-W and N-S with approximately 100 km of seismic sections obtained. Rates of sedimentation and seasonal fluctuation were determined. Sedimentation is dominated by the Godley River with sedimentation decreasing with distance from the delta of the Godley River.

In 1995, Smith *et al.* conducted a large scale seismic refraction velocity survey across the central South Island. This survey crossed through the Mackenzie Basin. The survey purpose was to model the crustal structure of the Australia-Pacific plate continent boundary to a depth of approximately 40 km. Explosions were detonated off each coast and in Lake Tekapo (Smith *et al.*, 1995). It was found that the P-wave velocity in the Triassic greywackes, which form part of the basement within the basin, were 5.4 km/s. These velocities were recorded to a depth of 2.7 km (Smith *et al.*, 1995).

In 1995, Stern also calculated gravity profiles from 50 years of existing data along the same line as the seismic refraction survey. Bouguer and isostatic gravity anomalies from the convergent plate boundary were developed using the seismic refraction data. Generally the gravity observations were based on basement rocks. However the Mackenzie Basin contains glacial till, gravels, and Tertiary sediments and their presence is thought to create localised negative residual gravity anomalies. The overall finding of the study is that the Bouguer gravity anomalies over the central South Island indicate subduction of 50-80 km of old oceanic lithosphere (Stern, 1995).

In 1995, a deep crustal seismic experiment was conducted along the eastern side of Lake Pukaki. The initial results presented by Davey *et al*. (1995) indicate reflections from a depth of approximately 25 km, suggesting a 40 ± 5º southeast dipping zone at 22 km beneath the Mt Cook village. It is thought that this reflector represents the extension of the Alpine Fault Zone.

Kleffman *et al*. (1998) conducted a smaller crustal structure investigation using explosion seismology measurements in 1995. One hundred and fourteen shots were fired in Lake Pukaki and recorded along a 27 km seismic reflection array on the eastern edge of Lake Pukaki, as well as a series of discrete seismographs forming an array 52 km in length. It was found that seismic waves travelling through the near surface glacial deposits were attenuated by scattering and affected by spatially variable delays due to variations in velocity and thickness of the glacial layer. A simple two layer velocity model was used (glacial deposits and greywacke basement) as no velocities indicative of Tertiary sediments were not found in the refraction data, suggesting that the Tertiary sediments are either thin or non-existent.

In 1998, a 65 km seismic reflection transect (SIGHT98) was shot from Burkes Pass in the southeast to Mt Cook village in the northeast to image the mohorovicic discontinuity and crustal root (Long *et al.*, 2003). Within the data collected was information regarding the shallow crust. The 1998 study provides the first detailed seismic image of the upper crust in this region. Numerous 2-3 km scale reflectors and discontinuities were defined and the nature of the Irishman Creek Fault was confirmed. It is suggested that a sequence of Late Cretaceous-Miocene sedimentary rocks may be present within the Mackenzie Basin, although this sequence is not found in surface outcrops within the Basin. There are no outcrops of this sequence. If the sedimentary deposits are present it is likely they will be less than 800 to 1200 m thick (assuming a 2 km/s minimum velocity, 1 km maximum thickness) (Long *et al.*, 2003). It is also noted that the only factor defining the difference between Pliocene-Pleistocene gravels (Glentanner Formation) and younger, late Quaternary sediments is the tilted dip of the Glentanner Formation (Long *et al.*, 2003). The thickness of the late Quaternary sediment is poorly constrained. As suggested by the velocity model of Kleffman *et al.* (1998) the late

Quaternary sediments thicken from ~600 m at the north of Lake Pukaki to ~800 m in the south of Lake Pukaki. The thickness of these sediments within the Mackenzie Basin is likely to be less than 1 km, based on topography and sediment fill within the lakes (Long *et al.,* 2003).

In conjunction with the larger SIGHT98 study a gravity survey was conducted along the same transect from Burkes Pass to Mt Cook Village by Chetwin (1998). The primary aim of the research was to model the subsurface structure of the basin, with emphasis on the Irishman Creek active fault. The Pliocene Glentanner Formation, dipping 60º to the south east was identified. The presence of a mud volcano is also mentioned and it is suggested that it has formed from carbonate sediment, possibly limestone, at depth. The presence of a Tertiary sequence (limestone) is inferred based on seismic reflection data (~1700 m depth) and work conducted in the Cannington Basin to the east of Burkes Pass. The velocities and densities used were derived from an adjacent work in the Cannington Basin by Langdale & Stern (1998) where velocities of the Plieocene-Pliestocene gravels was 2300 m/s and the density for these gravels was 2.30 Mg/m^3.

The seismic velocities are based on two shots from the SIGHT98 study, one on each side of the Irishman Creek Fault, which were also used to provide a control on the depth to basement. The density of the Pliocene and Pleistocene gravels was determined for use within the gravity model. A velocity of 2900 m/s is determined for the Pliocene Glentanner Formation, while the Pleistocene glacial gravels have a velocity of 2400 m/s. Refraction velocities indicate a limestone layer (4500 m/s) overlying the Torlesse basement (5600 m/s). The densities determined during the study for use within the gravity model were determined to be: Holocene alluvium 1.80 Mg/m^3, Pleistocene glacial deposits 2.15 Mg/m^3, Pliocene gravels 2.45 Mg/m^3, and Mesozoic greywacke and schist 2.67 Mg/m^3. The gravity model shows that steeply-dipping reverse faults are common, and that folding is also present within the basin (Chetwin, 1998).

The Alpine Fault and the area to the east have been further defined by Stern *et al.* (2007). An area approximately 45 by 20 km of low resistivity and low seismic velocity was identified and attributed to interconnected fluids at lithostatic pressure. It is suggested that the water is metamorphic dewatering of the schist-greywacke rocks that thicken into the orogen.

Fox (1987) used gravity data to define the extent of the Ostler and Irishman Creek Fault zones. Rough calculations of the negative gravity anomalies indicate that the surface to bedrock depth gradually increases from the northeast on the north side of the Old Man Range to the southwest near Lake Pukaki where bedrock is ~340 m below sea level. The surface of the basement is inferred to be irregular due to pre-Pleistocene tectonism and fluvial dissection. It is also suggested that the Irishman Creek Fault has a northeast extension based on the uplifted basement blocks of Mt John, Mt Hay, Wee McGregor, and possibly Motuariki Island in Lake Tekapo.

In 2001, a 61 km seismic survey of Lake Tekapo was shot to identify tectonic features observed onshore by Upton & Osterberg (2007). Bedrock highs (>70 m of relief) were identified along the strike of the Irishman Creek Fault and the Forest Creek Faults. The seismic data suggests that both of these faults extend into the centre of Lake Tekapo but do not reach the opposite shore. Instead they terminate against a north-south structure, which Long *et al.* (2003) suggest is the Tekapo River Fault. The bedrock highs, lake floor offsets, and mass movement deposits are interpreted to be the result of tectonic uplift and paleoearthquake events.

The Ostler Fault was investigated by Wallace (2002) as part of a larger study aimed at developing a knowledge of the near surface characteristics of thrust faults in the Mackenzie Basin. Ground Penetrating Radar (GPR) and resistivity tomography were used to detail subsurface features by creating both 2D and 3D models. The models were used to define the subsurface morphology of a portion of the Ostler Fault Zone. Fault splays, buried channels and drainage patterns have all been identified in the subsurface. It is noted that the upward deformation of the Ostler Fault has produced changes in the drainage pattern across the fault zone. The Benmore segment of the GPR survey has also identified at least one perched water table that has a spring as its surface expression.

Additional GPR surveys were carried out by Nobes *et al.* (2003), from which thrust fault splays were identified to the east of the west-dipping Ruataniwha Fault. In 2006, a subsequent GPR and resistivity tomography survey was conducted across the Ruataniwha segment of the Ostler Fault Zone. Lapwood (2006) suggests that the GPR profiles from the Nobes *et al.* (2003) study may have been misinterpreted, and suggest that the sides of paleochannels can give the same geophysical response as faults bounded by a loess wedge. In conjunction with the geophysical surveys, a trench was dug to a 5 m depth. The trench has also been logged in detail. The trench is within the Mt John Formation, and illustrates the highly variable nature of the formation. Water bearing, mud rich lenses were encountered at the bottom of the trench.

In 2006, a seismic survey was conducted across the Ostler Fault Zone to the south of Twizel by Ghisetti *et al.* (2007). A new geological and morphotectonic map of the southern Ostler Fault Zone is presented. The primary aim of the study is to delineate the geometry and kinematics of the subsurface. As a result, the interpretation is that the Ostler Fault propagated up-dip across the Pliocene Quaternary terrestrial sequence as the high angle splay of a Late Cretaceous Paleocene normal fault that has undergone cycles of compressional reactivation in the last 2.4 Ma (Ghisetti *et al.*, 2007). It is suggested that the gravimetric low in the east of the Mackenzie Basin, identified by Kleffman & Stern (unpublished) may indicate the presence of a trough buried below the Pleistocene gravels of the western part of the basin which has been filled with up to 1600 m of sediments. As the maximum estimated thickness of the Plio-Quaternary is <800 m, older Tertiary sediment could be present in a thicker basin (Ghisetti *et al.*, 2007). The seismic work carried out along the Lake Ohau Road shows weak reflections extending to depths below 1 km, but they were not distinct from the seismic velocities of the Torlesse basement.

The kinematics of surface deformation and the slip rates along the Ostler Fault and Irishman Creek Fault have also been studied by Amos *et al.* (2007). The deformation of fluvial terraces preserved over active thrust-related folds is used to interpret both of the faults as listric thrusts. Detailed topographic surveying of the deformed terraces combined with Ground Penetrating Radar and luminescence dating of the terrace surfaces has provided slip rates of the Ostler Fault to be ~1.1-1.7 mm/yr and ~0.5-0.7 mm/yr for the Irishman Creek Fault. Further investigation of channel morphology was carried out to determine the channel width response to differential uplift in rivers. As a comparison buried channel topography was also investigated revealing a complex bar and braided channel geometry at depth with steep-walled banks (Amos & Burbank, 2007).

Appendix 3B

Gravity Theory and Gravity Corrections - Methods

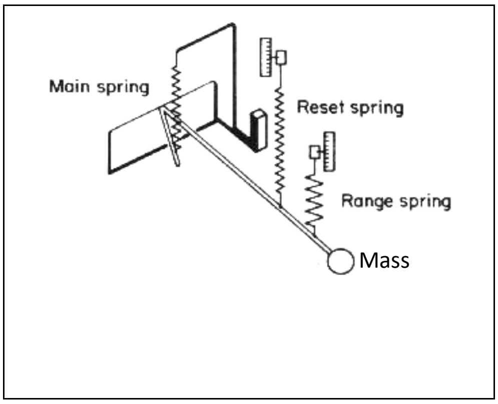
1. Gravity Theory

The equipotential surface used, where *U* is a constant, is the sea level surface of the Earth (or geoid), which is horizontal and orthogonal to the direction of gravity. The mean value of gravity on the Earth's surface is ~9.80 ms^{-2}. When surveying on land, an accuracy of ±0.1 gu (gu = gravity unit) is attainable and is equal to approximately one hundred millionth of the normal gravitational field (Kearey & Brooks, 1991). Gravity can be affected at differing levels by surface and subsurface features. For example, Mount Everest which creates a difference of ~20,000 gu or a sedimentary basin which can reduce the gravity field by more than 1,000 gu (Milsom, 2003).

Generally, the difference in gravity between locations is measured. Gravimeters (such as the Worden Gravity Meter) are used to measure gravity and consist of spring balances carrying a constant mass. Variations in the weight of the mass due to variations in gravity cause the length of the spring to vary and measure the change in gravity at each location (Kearey & Brooks, 1991). The internal structure of the Worden gravimeter is illustrated in Figure 1. The Worden gravimeter consists of two springs where one acts as the measuring device and the second changes the level of the 2000 gu reading range of the meter and an accuracy of 0.1 – 0.2 gu (Parasnis, 1986; Kearey & Brooks, 1991). The gravimeter can be made to have an unstable equilibrium causing the meter to be very sensitive to variations in gravity (Parasnis, 1986).

A

B



C

Figure 1: (A) Worden gravimeter used in survey; (B) Dials of gravimeter; (C) Diagram of the internal structure of the unstable Worden gravimeter. By adjusting the reset spring the mass is restored to its standard position and a measurement can be made (Parasnis, 1986).

2. Gravity Corrections

2.1 Instrument Drift Correction

Instrument drift causes gradual changes in readings at a single location and is due to elastic creep of the springs within the meter as well as temperature variations causing expansion and contraction of the meter (Parasnis, 1986; Kearey & Brooks, 1991). Drift corrections are made by frequently returning to a set base station within the survey area.

While running a gravity survey the latitude and elevation of each station is required with a high degree of accuracy. 'Looping' back to selected base stations (or a station with a known absolute gravity value) between stations is required to correct for drift during the survey.

To correct for drift the meter readings are plotted against time. The drift correction at time 't' is 'd', which is then subtracted from the observed value (Kearey & Brooks, 1991) (2).

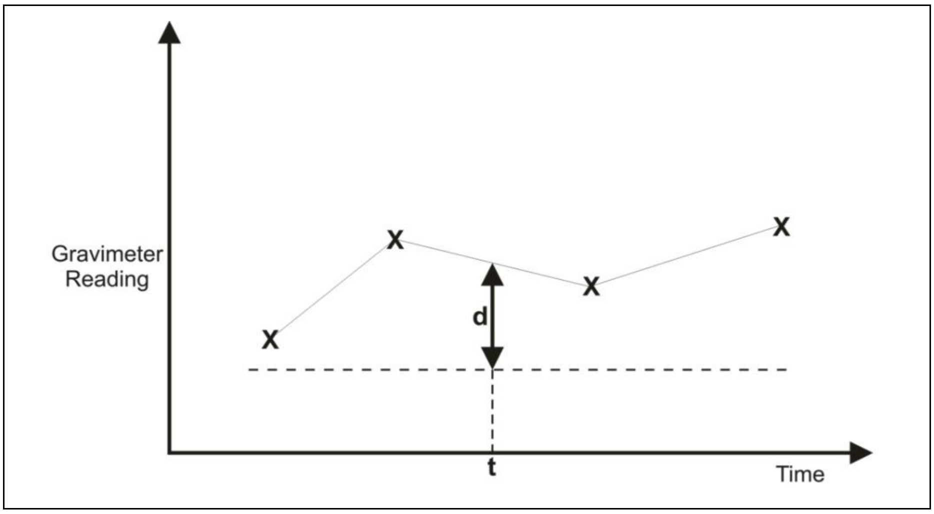


Figure 2: Base station drift correction – the drift correction subtracted for a reading taken at time '*t*' is '*d*' (Kearey & Brooks, 1991).

Following the drift correction the difference in gravity between the base station and observation stations is determined by multiplying the difference in the meter reading by the calibration factor of the gravimeter. This enables the absolute gravity of the observation station (g_{obs}) to be calculated from the known value of the gravity at the base station (Kearey & Brooks, 1991).

2.2 Latitude Variations

Due to the ellipsoidal shape of the Earth and the decreasing velocity of a point towards the poles, gravity varies with latitude. There is a variation of 5,000 millgals (mGal) (1 mGal = 10^{-5}

m/sec^{-2}) between the poles and the equator. Gravity can be related to latitude using the Gravity Formula 1967:

$g_\Phi = g_0(1 + k_1 \sin^2\Phi - k_2 \sin^2 2\Phi)$	$k_1 = 0.0053024$ $k_2 = 0.0000059$ g_Φ = predicted value of gravity at latitude Φ g_0 = value of gravity at the equator k_1 and k_2 = constants (dependent on shape and speed of rotation of Earth)

g_Φ is the predicted value of gravity at sea level at any point on the Earth's surface within 1 µms^{-2}. This value is then subtracted from the gravity at observed stations to correct for variations in latitude (Parasnis, 1986).

2.3 Free-air Correction

The Free-air correction (g_{FA}) is required to account for gravity variations caused by elevation differences in the observation locations (Figure 3). Gravity will decrease with height in free air with increased distance from the centre of the Earth. The observed gravitational effect decreases at a rate of 0.3086 mGal/m. The following equations is used to correct the observed data:

$$g_{FA} = gobs - gn + 0.3086\ h\ (mgal)$$

g_{obs}=observed gravity g_n=latitude correction h=station elevation above sea level

Elevations above sea level are added to the datum and elevations below sea level are subtracted from the datum. The differential GPS uses mean sea level as the common datum and therefore elevations were added to the datum.

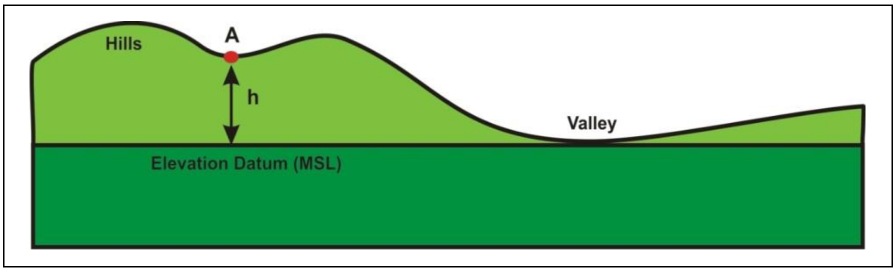


Figure 3: Free air correction for observation point A at a height (h) above the elevation datum. The height of A above the elevation datum (usually mean sea level) needs to be deducted so that each observation point is assumed to be on a flat surface.

2.4 Bouguer Correction

The Bouguer correction (g_b) is required to remove the effect of excess masses underlying observation points located at elevations higher than the elevation datum, or mass deficiencies below the elevation datum. The Bouguer correction approximates the rock layer beneath the observation station to an infinite horizontal slab with a thickness equal to the elevation of the observation above datum, on land the correction is subtracted (Figure 4) (Kearey & Brooks, 1991). The equation used for the Bouguer correction is:

$$g_b = g_{obs} - g_n + 0.3086\ h - 0.04193\ \rho\, h\ (mgal)$$

ρ = average density of rocks

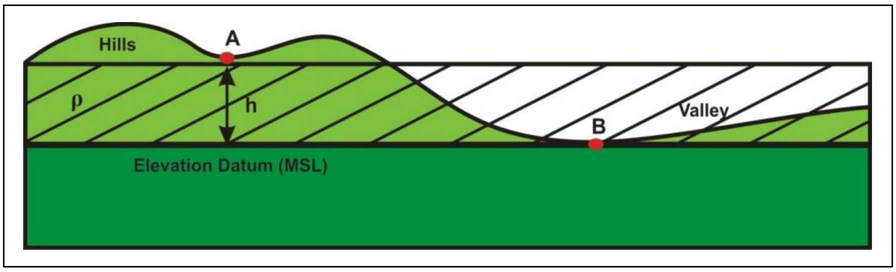


Figure 4: Bouguer correction – gravity anomaly determined by approximating the mass beneath the observation point (A) as a slab of material with thickness h and density ρ.

2.5 Terrain Correction

To correct for topography surrounding observation stations a Terrain correction (g_t) must be applied, the correction is positive (Figure 5). Terrain corrections are usually made using a circular graticule known as a Hammer chart (see Kearey & Brooks (1991) for further detail). Where the topography is generally flat lying, such as within the Mackenzie Basin, terrain effects are generally low (<10 gu). Where this value is less than the preferred accuracy of the survey, the terrain correction can be ignored (Kearey & Brooks, 1991). Terrain corrections were not applied to this survey due to the flat lying nature of the survey area.

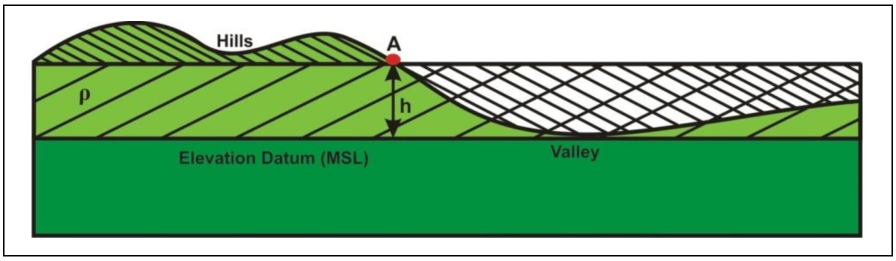


Figure 5: Terrain correction removes the effects of hills and valleys surrounding th observation point (A).

2.6 Tide Corrections

The effect of the tides (oceanic and solid Earth shape) can cause the elevation of an observation point to change by a few centimetres. The gravity variations have a maximum amplitude of 3 gu and a minimum period of 12 hours. Surveys with base ties with smaller intervals than 12 hours automatically remove the variations of tides during drift corrections, therefore tidal corrections were not needed for this survey (Kearey & Brooks, 1991).

Appendix 3C

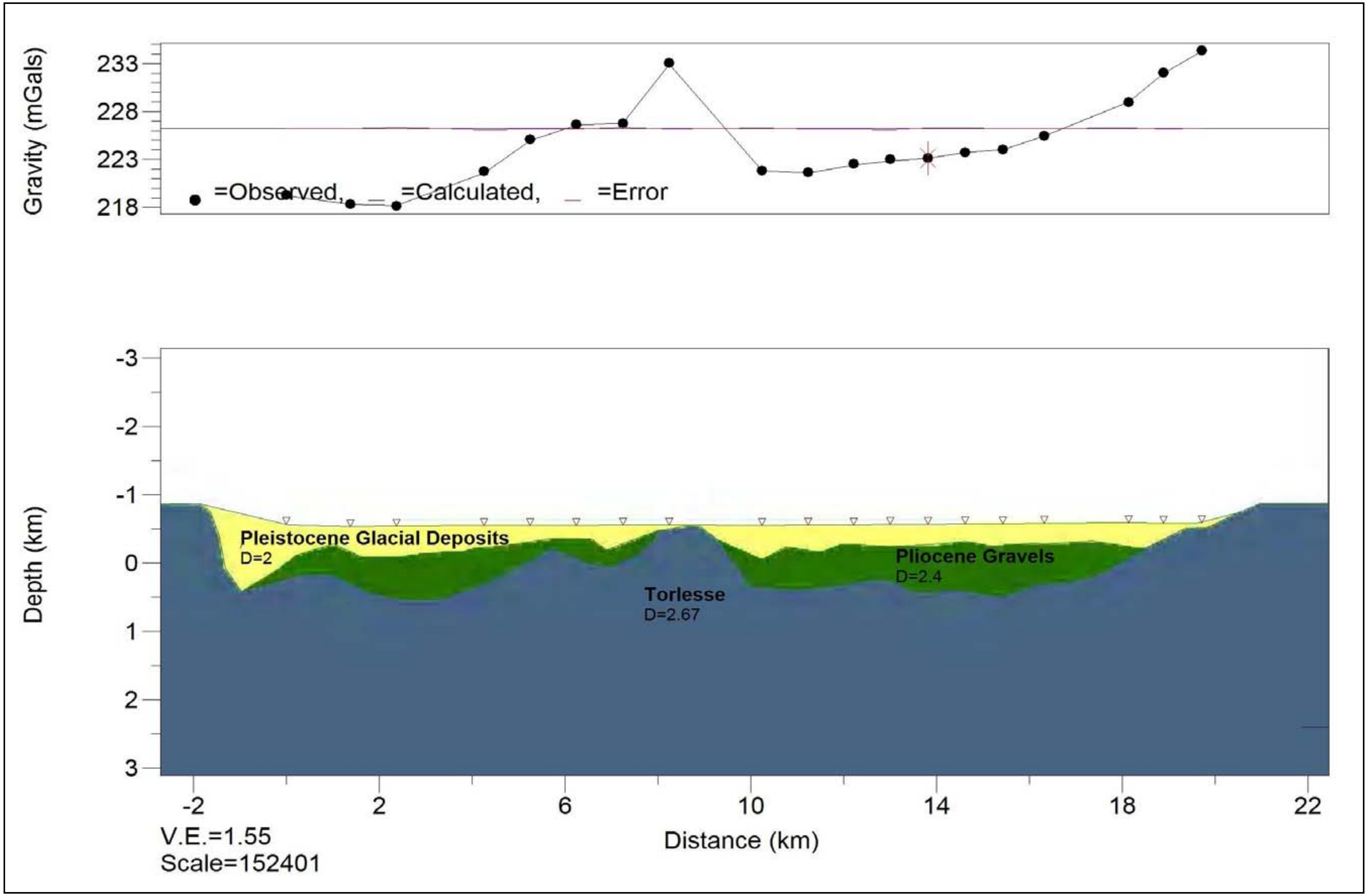
Gravity Data and Corrections

Gravity Data, Corrections and Results

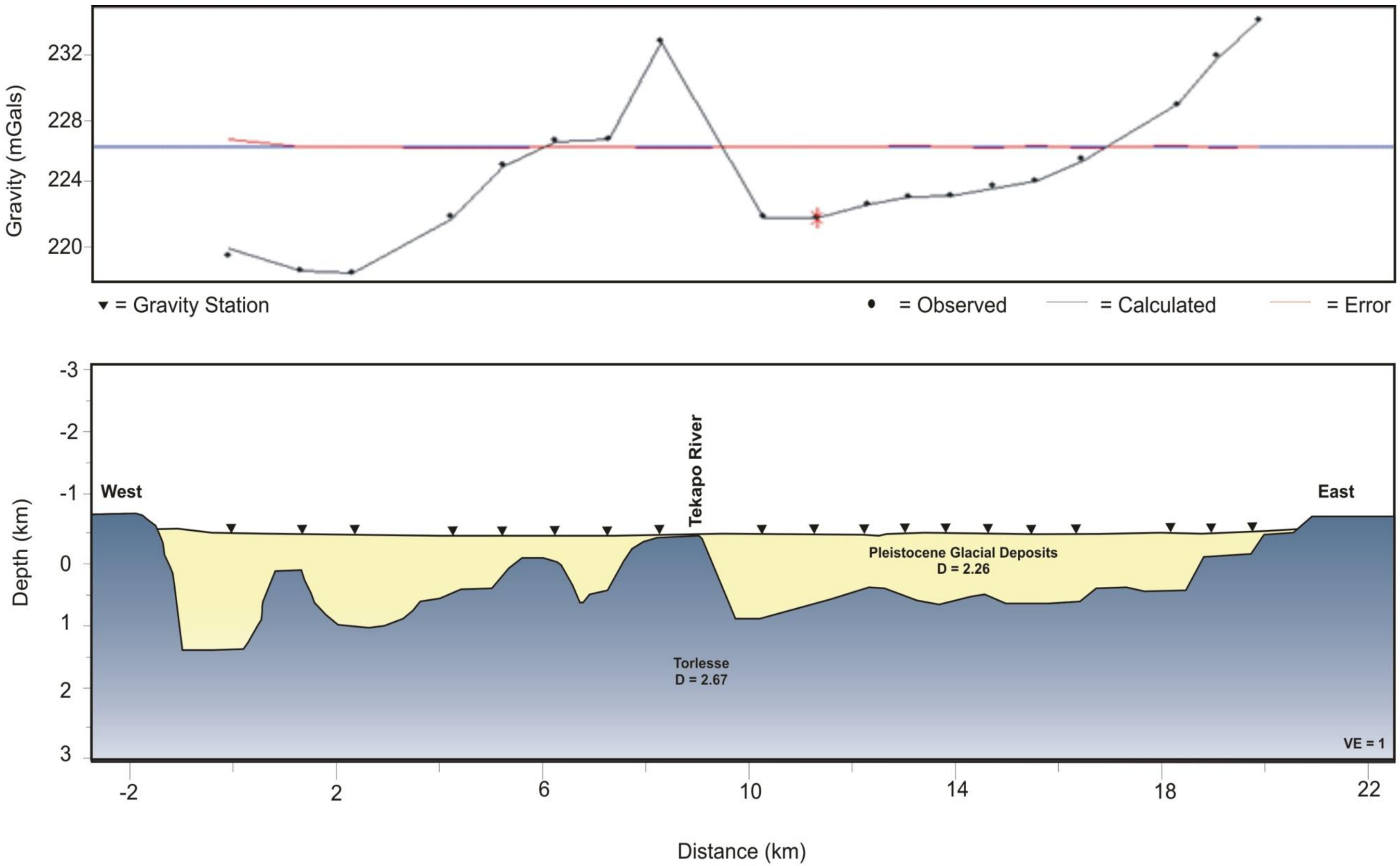
Gravity Data													Data Corrections				Corrected Data	
Station	Day	Time	Distance from Start of Line (m)	Elevation (m)	Reading 1	Reading 2	Reading 3	Average Reading	Gravity (mGal)	Standard Deviation (mGal)	Northing	Latitude	Latitude	Free Air	Bouguer	Terrain	Corrected Gravity (mGal)	Anomaly
4	2	12:12:31	0.0	567.1	1216.0	1215.0	1214.0	1214.8	108.2	0.083	5669309	-44.152	0.42	175.0	63.5	0	219.3	1.1
3	2	11:12:17	1377.6	536.2	1272.1	1274.0	1272.1	1272.7	113.3	0.100	5669315	-44.153	0.43	165.5	60.0	0	218.3	0.2
2	2	10:44:13	2374.1	547.5	1247.0	1247.1	1246.1	1246.7	111.0	0.051	5669454	-44.152	0.54	169.0	61.3	0	218.1	0.0
1a	2	13:40:55	4252.7	551.5	1280.1	1280.1	1279.1	1279.7	114.0	0.050	5669594	-44.151	0.65	170.2	61.7	0	221.8	3.6
2a	2	13:52:00	5252.2	551.5	1316.0	1315.1	1316.0	1315.7	117.2	0.050	5669486	-44.152	0.57	170.2	61.7	0	225.1	6.9
3a	2	14:05:20	6249.9	554.1	1326.1	1328.0	1326.1	1326.7	118.1	0.100	5669377	-44.153	0.48	171.0	62.0	0	226.6	8.5
4a	2	14:42:23	7255.2	558.5	1317.1	1317.1	1317.0	1317.1	117.3	0.002	5669267	-44.155	0.39	172.4	62.5	0	226.7	8.6
5a	2	14:56:05	8251.6	561.5	1382.0	1381.1	1381.0	1381.4	123.0	0.050	5669284	-44.155	0.40	173.3	62.9	0	233.0	14.9
1b	1	14:18:01	10239.6	555.1	1265.0	1268.0	1267.0	1266.7	112.8	0.137	5668963	-44.158	0.15	171.3	62.1	0	221.8	3.7
2b	1	14:00:45	11245.0	557.7	1259.0	1259.0	1259.0	1259.0	112.1	0.001	5668937	-44.159	0.13	172.1	62.4	0	221.7	3.5
3b	1	13:32:56	12219.2	559.8	1259.0	1259.1	1261.0	1262.9	112.5	0.089	5668780	-44.160	0.00	172.7	62.7	0	222.5	4.4
4b	1	13:09:02	13001.3	566.4	1258.0	1259.0	1257.1	1258.0	112.0	0.086	5669293	-44.156	0.41	174.8	63.4	0	223.0	4.8
5b	1	12:52:35	13816.7	570.3	1258.1	1255.1	1256.1	1256.4	111.9	0.134	5669901	-44.151	0.90	176.0	63.8	0	223.1	5.0
6b	1	12:05:06	14619.1	575.1	1257.0	1258.0	1258.0	1257.7	112.0	0.051	5670496	-44.146	1.37	177.5	64.4	0	223.7	5.6
7b	1	11:49:16	15438.8	579.6	1256.1	1259.0	1256.0	1257.1	111.9	0.153	5671166	-44.140	1.91	178.9	64.9	0	224.0	5.9
8b	1	11:34:07	16322.8	585.1	1268.0	1266.1	1266.1	1266.7	112.8	0.101	5671778	-44.135	2.40	180.5	65.5	0	225.5	7.3
10b	1	15:24:31	18146.6	593.5	1298.0	1297.0	1297.1	1297.4	115.5	0.050	5672909	-44.125	3.30	183.2	66.4	0	228.9	10.8
11b	1	15:40:56	18895.7	589.6	1338.0	1339.1	1339.0	1338.7	119.2	0.051	5672657	-44.127	3.10	181.9	66.0	0	232.0	13.9
12b	1	16:01:59	19718.6	591.3	1359.1	1359.0	1359.1	1359.1	121.0	0.001	5672478	-44.129	2.96	182.5	66.2	0	234.3	16.2

Appendix 3D

Alternative Gravity Models



Alternative models can represent the same data – here the densities have been altered in the overlying gravels changing their thickness.



Alternative models can represent the same data – here the Pliocene gravels have been removed completely and the density of the Pleistocene gravels has been increased.

Appendix 3E

TEM Equivalence Models

(see attached CD)

Appendix 3F

Stages in Seismic Processing

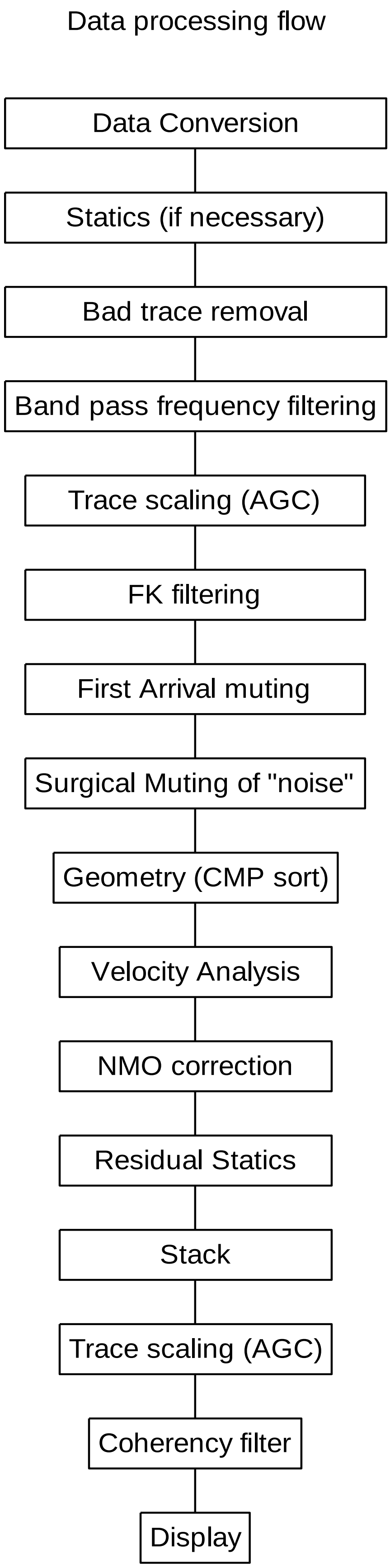


Figure 1: Key stages in seismic processing (Finnemore, 2004)

During seismic data processing several assumptions/principles are used (Table 1).

Table 1: Assumptions made during processing (modified from Anderson, 2000; Finnemore, 2004).

1. The subsurface can be subdivided into layers of effectively uniform density and seismic velocity – referred to as acoustic impedance. Layers of uniform acoustic impedance are generally separated by the water table, bedrock, lithologic contacts, or unconformable surfaces.
2. Body wave energy is sent into the subsurface via a seismic source. The body waves are compressional (p-waves) – parallel to wave propagation and shear (s-waves) – perpendicular to the wave propagation.
3. The velocity of a wave front of either p-waves or s-waves is a determined by the properties of the subsurface through which the waves passes which can range from <200 m/s to 8500 m/s for P-waves and less from s-waves.
4. Seismic wavelets can be characterised by their maximum amplitude, dominant frequency, and wavelength.
5. When a ray path is incident on a layer boundary the energy will be reflected and refracted according to Snell's Law and p-waves may convert to s-waves (or vice versa).
6. Zoeppritz equations are used to calculate the relative amplitudes of reflected and transmitted wavelets.
7. A stacked (migrated) profile is made from a group of individual traces. Ray paths are assumed to be vertical, to have coincident sources/receivers located at the CMP, and have been vertically incident on underlying reflecting horizons. The two-way travel time to a seismic event is a direct function of vertical depth and average velocity to that boundary. The relative magnitude of a seismic event is a direct function of the magnitude of the corresponding vertical incidence reflection coefficient.
8. The process of migration converts non-migrated data to migrated data. In non-migrated (stacked) data, ray paths are assumed to be normally incident on layer boundaries. Also, reflected data from dipping surfaces are not displayed in their correct spatial locations and diffracted energy is not placed at its correct spatial point of origin.

The assumptions made during this survey were:

1. This is a simple 2D model.
2. That the upper layer has a slower velocity than the underlying layer ($V_1<V_2$).
3. That the direct P-wave velocity is V_1 and the refracted P-wave velocity is V_2. The crossover distance method is being used to determine the point of change from one velocity to another.
4. That the layer is horizontal at the scale we are interested in.
5. That the topography does not have any dramatic effects on the results

Appendix 3G

Selected Seismic Profiles Used for Seismic Refraction Model

(see attached CD)

Appendix 3H

Data for Seismic Refraction Model

Summary of Velocities used in Seismic Refraction Calculations

Field Record (#fldr)	Velocity 1 (V_1) (m/s)	Velocity 2 (V_2) (m/s)	Cross Over Distance - Xc (m)	Thickness of Layer - h (m)
102	896	4314	65	26.32
105	960	3014	68	24.44
106	1028	3328	54	19.62
112	960	3120	57	20.74
113	834	3300	50	19.31
119	808	2816	49	18.24
124	698	2506	21	7.89
130	1474	2756	50	13.76
135	1284	2322	49	13.14
141	1378	2344	36	9.17
146	1776	3132	28	33.64
152	1810	3366	169	46.33
158	1762	2720	169	39.07
163	2018	2772	180	35.71
168	2032	2566	110	18.74
173	2060	2748	169	31.96
176	1864	2616	85	17.41
183	1572	2230	100	20.80
188	1636	2364	60	12.80

Appendix 3I

Data for Seismic Reflection Profile

Reflection refraction calculation Spreadsheet

Critical angle			h	50
30			Vp1	1000
First refraction			Vp2	2000
57.7				

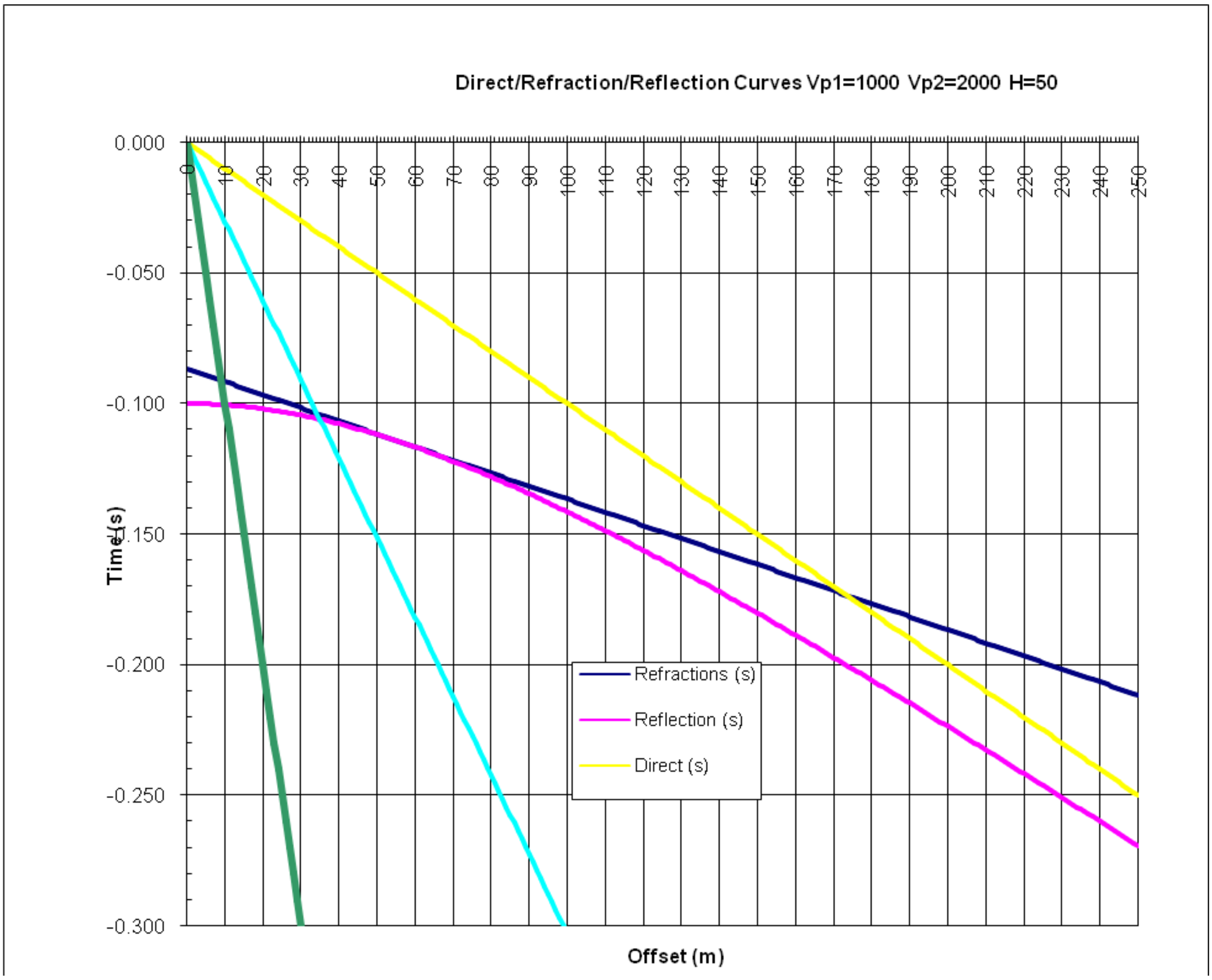
x (m)	Refractions (s)	Reflection (s)	Direct (s)	Airwave (s)	Rayleigh waves (s)
0	-0.087	-0.100	0.000	0.000	0.000
1	-0.087	-0.100	-0.001	-0.003	-0.010
2	-0.088	-0.100	-0.002	-0.006	-0.020
3	-0.088	-0.100	-0.003	-0.009	-0.030
4	-0.089	-0.100	-0.004	-0.012	-0.040
5	-0.089	-0.100	-0.005	-0.015	-0.050
6	-0.090	-0.100	-0.006	-0.018	-0.060
7	-0.090	-0.100	-0.007	-0.021	-0.070
8	-0.091	-0.100	-0.008	-0.024	-0.080
9	-0.091	-0.100	-0.009	-0.027	-0.090
10	-0.092	-0.100	-0.010	-0.030	-0.100
11	-0.092	-0.101	-0.011	-0.033	-0.110
12	-0.093	-0.101	-0.012	-0.036	-0.120
13	-0.093	-0.101	-0.013	-0.039	-0.130
14	-0.094	-0.101	-0.014	-0.042	-0.140
15	-0.094	-0.101	-0.015	-0.045	-0.150
16	-0.095	-0.101	-0.016	-0.048	-0.160
17	-0.095	-0.101	-0.017	-0.052	-0.170
18	-0.096	-0.102	-0.018	-0.055	-0.180
19	-0.096	-0.102	-0.019	-0.058	-0.190
20	-0.097	-0.102	-0.020	-0.061	-0.200
21	-0.097	-0.102	-0.021	-0.064	-0.210
22	-0.098	-0.102	-0.022	-0.067	-0.220
23	-0.098	-0.103	-0.023	-0.070	-0.230
24	-0.099	-0.103	-0.024	-0.073	-0.240
25	-0.099	-0.103	-0.025	-0.076	-0.250
26	-0.100	-0.103	-0.026	-0.079	-0.260
27	-0.100	-0.104	-0.027	-0.082	-0.270
28	-0.101	-0.104	-0.028	-0.085	-0.280
29	-0.101	-0.104	-0.029	-0.088	-0.290
30	-0.102	-0.104	-0.030	-0.091	-0.300
31	-0.102	-0.105	-0.031	-0.094	-0.310
32	-0.103	-0.105	-0.032	-0.097	-0.320
33	-0.103	-0.105	-0.033	-0.100	-0.330
34	-0.104	-0.106	-0.034	-0.103	-0.340
35	-0.104	-0.106	-0.035	-0.106	-0.350
36	-0.105	-0.106	-0.036	-0.109	-0.360
37	-0.105	-0.107	-0.037	-0.112	-0.370
38	-0.106	-0.107	-0.038	-0.115	-0.380
39	-0.106	-0.107	-0.039	-0.118	-0.390
40	-0.107	-0.108	-0.040	-0.121	-0.400
41	-0.107	-0.108	-0.041	-0.124	-0.410
42	-0.108	-0.108	-0.042	-0.127	-0.420
43	-0.108	-0.109	-0.043	-0.130	-0.430
44	-0.109	-0.109	-0.044	-0.133	-0.440

45	-0.109	-0.110	-0.045	-0.136	-0.450
46	-0.110	-0.110	-0.046	-0.139	-0.460
47	-0.110	-0.110	-0.047	-0.142	-0.470
48	-0.111	-0.111	-0.048	-0.145	-0.480
49	-0.111	-0.111	-0.049	-0.148	-0.490
50	-0.112	-0.112	-0.050	-0.152	-0.500
51	-0.112	-0.112	-0.051	-0.155	-0.510
52	-0.113	-0.113	-0.052	-0.158	-0.520
53	-0.113	-0.113	-0.053	-0.161	-0.530
54	-0.114	-0.114	-0.054	-0.164	-0.540
55	-0.114	-0.114	-0.055	-0.167	-0.550
56	-0.115	-0.115	-0.056	-0.170	-0.560
57	-0.115	-0.115	-0.057	-0.173	-0.570
58	-0.116	-0.116	-0.058	-0.176	-0.580
59	-0.116	-0.116	-0.059	-0.179	-0.590
60	-0.117	-0.117	-0.060	-0.182	-0.600
61	-0.117	-0.117	-0.061	-0.185	-0.610
62	-0.118	-0.118	-0.062	-0.188	-0.620
63	-0.118	-0.118	-0.063	-0.191	-0.630
64	-0.119	-0.119	-0.064	-0.194	-0.640
65	-0.119	-0.119	-0.065	-0.197	-0.650
66	-0.120	-0.120	-0.066	-0.200	-0.660
67	-0.120	-0.120	-0.067	-0.203	-0.670
68	-0.121	-0.121	-0.068	-0.206	-0.680
69	-0.121	-0.121	-0.069	-0.209	-0.690
70	-0.122	-0.122	-0.070	-0.212	-0.700
71	-0.122	-0.123	-0.071	-0.215	-0.710
72	-0.123	-0.123	-0.072	-0.218	-0.720
73	-0.123	-0.124	-0.073	-0.221	-0.730
74	-0.124	-0.124	-0.074	-0.224	-0.740
75	-0.124	-0.125	-0.075	-0.227	-0.750
76	-0.125	-0.126	-0.076	-0.230	-0.760
77	-0.125	-0.126	-0.077	-0.233	-0.770
78	-0.126	-0.127	-0.078	-0.236	-0.780
79	-0.126	-0.127	-0.079	-0.239	-0.790
80	-0.127	-0.128	-0.080	-0.242	-0.800
81	-0.127	-0.129	-0.081	-0.245	-0.810
82	-0.128	-0.129	-0.082	-0.248	-0.820
83	-0.128	-0.130	-0.083	-0.252	-0.830
84	-0.129	-0.131	-0.084	-0.255	-0.840
85	-0.129	-0.131	-0.085	-0.258	-0.850
86	-0.130	-0.132	-0.086	-0.261	-0.860
87	-0.130	-0.133	-0.087	-0.264	-0.870
88	-0.131	-0.133	-0.088	-0.267	-0.880
89	-0.131	-0.134	-0.089	-0.270	-0.890
90	-0.132	-0.135	-0.090	-0.273	-0.900
91	-0.132	-0.135	-0.091	-0.276	-0.910
92	-0.133	-0.136	-0.092	-0.279	-0.920
93	-0.133	-0.137	-0.093	-0.282	-0.930
94	-0.134	-0.137	-0.094	-0.285	-0.940
95	-0.134	-0.138	-0.095	-0.288	-0.950
96	-0.135	-0.139	-0.096	-0.291	-0.960
97	-0.135	-0.139	-0.097	-0.294	-0.970
98	-0.136	-0.140	-0.098	-0.297	-0.980

99	-0.136	-0.141	-0.099	-0.300	-0.990
100	-0.137	-0.141	-0.100	-0.303	-1.000
101	-0.137	-0.142	-0.101	-0.306	-1.010
102	-0.138	-0.143	-0.102	-0.309	-1.020
103	-0.138	-0.144	-0.103	-0.312	-1.030
104	-0.139	-0.144	-0.104	-0.315	-1.040
105	-0.139	-0.145	-0.105	-0.318	-1.050
106	-0.140	-0.146	-0.106	-0.321	-1.060
107	-0.140	-0.146	-0.107	-0.324	-1.070
108	-0.141	-0.147	-0.108	-0.327	-1.080
109	-0.141	-0.148	-0.109	-0.330	-1.090
110	-0.142	-0.149	-0.110	-0.333	-1.100
111	-0.142	-0.149	-0.111	-0.336	-1.110
112	-0.143	-0.150	-0.112	-0.339	-1.120
113	-0.143	-0.151	-0.113	-0.342	-1.130
114	-0.144	-0.152	-0.114	-0.345	-1.140
115	-0.144	-0.152	-0.115	-0.348	-1.150
116	-0.145	-0.153	-0.116	-0.352	-1.160
117	-0.145	-0.154	-0.117	-0.355	-1.170
118	-0.146	-0.155	-0.118	-0.358	-1.180
119	-0.146	-0.155	-0.119	-0.361	-1.190
120	-0.147	-0.156	-0.120	-0.364	-1.200
121	-0.147	-0.157	-0.121	-0.367	-1.210
122	-0.148	-0.158	-0.122	-0.370	-1.220
123	-0.148	-0.159	-0.123	-0.373	-1.230
124	-0.149	-0.159	-0.124	-0.376	-1.240
125	-0.149	-0.160	-0.125	-0.379	-1.250
126	-0.150	-0.161	-0.126	-0.382	-1.260
127	-0.150	-0.162	-0.127	-0.385	-1.270
128	-0.151	-0.162	-0.128	-0.388	-1.280
129	-0.151	-0.163	-0.129	-0.391	-1.290
130	-0.152	-0.164	-0.130	-0.394	-1.300
131	-0.152	-0.165	-0.131	-0.397	-1.310
132	-0.153	-0.166	-0.132	-0.400	-1.320
133	-0.153	-0.166	-0.133	-0.403	-1.330
134	-0.154	-0.167	-0.134	-0.406	-1.340
135	-0.154	-0.168	-0.135	-0.409	-1.350
136	-0.155	-0.169	-0.136	-0.412	-1.360
137	-0.155	-0.170	-0.137	-0.415	-1.370
138	-0.156	-0.170	-0.138	-0.418	-1.380
139	-0.156	-0.171	-0.139	-0.421	-1.390
140	-0.157	-0.172	-0.140	-0.424	-1.400
141	-0.157	-0.173	-0.141	-0.427	-1.410
142	-0.158	-0.174	-0.142	-0.430	-1.420
143	-0.158	-0.174	-0.143	-0.433	-1.430
144	-0.159	-0.175	-0.144	-0.436	-1.440
145	-0.159	-0.176	-0.145	-0.439	-1.450
146	-0.160	-0.177	-0.146	-0.442	-1.460
147	-0.160	-0.178	-0.147	-0.445	-1.470
148	-0.161	-0.179	-0.148	-0.448	-1.480
149	-0.161	-0.179	-0.149	-0.452	-1.490
150	-0.162	-0.180	-0.150	-0.455	-1.500
151	-0.162	-0.181	-0.151	-0.458	-1.510
152	-0.163	-0.182	-0.152	-0.461	-1.520

153	-0.163	-0.183	-0.153	-0.464	-1.530
154	-0.164	-0.184	-0.154	-0.467	-1.540
155	-0.164	-0.184	-0.155	-0.470	-1.550
156	-0.165	-0.185	-0.156	-0.473	-1.560
157	-0.165	-0.186	-0.157	-0.476	-1.570
158	-0.166	-0.187	-0.158	-0.479	-1.580
159	-0.166	-0.188	-0.159	-0.482	-1.590
160	-0.167	-0.189	-0.160	-0.485	-1.600
161	-0.167	-0.190	-0.161	-0.488	-1.610
162	-0.168	-0.190	-0.162	-0.491	-1.620
163	-0.168	-0.191	-0.163	-0.494	-1.630
164	-0.169	-0.192	-0.164	-0.497	-1.640
165	-0.169	-0.193	-0.165	-0.500	-1.650
166	-0.170	-0.194	-0.166	-0.503	-1.660
167	-0.170	-0.195	-0.167	-0.506	-1.670
168	-0.171	-0.196	-0.168	-0.509	-1.680
169	-0.171	-0.196	-0.169	-0.512	-1.690
170	-0.172	-0.197	-0.170	-0.515	-1.700
171	-0.172	-0.198	-0.171	-0.518	-1.710
172	-0.173	-0.199	-0.172	-0.521	-1.720
173	-0.173	-0.200	-0.173	-0.524	-1.730
174	-0.174	-0.201	-0.174	-0.527	-1.740
175	-0.174	-0.202	-0.175	-0.530	-1.750
176	-0.175	-0.202	-0.176	-0.533	-1.760
177	-0.175	-0.203	-0.177	-0.536	-1.770
178	-0.176	-0.204	-0.178	-0.539	-1.780
179	-0.176	-0.205	-0.179	-0.542	-1.790
180	-0.177	-0.206	-0.180	-0.545	-1.800
181	-0.177	-0.207	-0.181	-0.548	-1.810
182	-0.178	-0.208	-0.182	-0.552	-1.820
183	-0.178	-0.209	-0.183	-0.555	-1.830
184	-0.179	-0.209	-0.184	-0.558	-1.840
185	-0.179	-0.210	-0.185	-0.561	-1.850
186	-0.180	-0.211	-0.186	-0.564	-1.860
187	-0.180	-0.212	-0.187	-0.567	-1.870
188	-0.181	-0.213	-0.188	-0.570	-1.880
189	-0.181	-0.214	-0.189	-0.573	-1.890
190	-0.182	-0.215	-0.190	-0.576	-1.900
191	-0.182	-0.216	-0.191	-0.579	-1.910
192	-0.183	-0.216	-0.192	-0.582	-1.920
193	-0.183	-0.217	-0.193	-0.585	-1.930
194	-0.184	-0.218	-0.194	-0.588	-1.940
195	-0.184	-0.219	-0.195	-0.591	-1.950
196	-0.185	-0.220	-0.196	-0.594	-1.960
197	-0.185	-0.221	-0.197	-0.597	-1.970
198	-0.186	-0.222	-0.198	-0.600	-1.980
199	-0.186	-0.223	-0.199	-0.603	-1.990
200	-0.187	-0.224	-0.200	-0.606	-2.000
201	-0.187	-0.225	-0.201	-0.609	-2.010
202	-0.188	-0.225	-0.202	-0.612	-2.020
203	-0.188	-0.226	-0.203	-0.615	-2.030
204	-0.189	-0.227	-0.204	-0.618	-2.040
205	-0.189	-0.228	-0.205	-0.621	-2.050
206	-0.190	-0.229	-0.206	-0.624	-2.060

207	-0.190	-0.230	-0.207	-0.627	-2.070
208	-0.191	-0.231	-0.208	-0.630	-2.080
209	-0.191	-0.232	-0.209	-0.633	-2.090
210	-0.192	-0.233	-0.210	-0.636	-2.100
211	-0.192	-0.233	-0.211	-0.639	-2.110
212	-0.193	-0.234	-0.212	-0.642	-2.120
213	-0.193	-0.235	-0.213	-0.645	-2.130
214	-0.194	-0.236	-0.214	-0.648	-2.140
215	-0.194	-0.237	-0.215	-0.652	-2.150
216	-0.195	-0.238	-0.216	-0.655	-2.160
217	-0.195	-0.239	-0.217	-0.658	-2.170
218	-0.196	-0.240	-0.218	-0.661	-2.180
219	-0.196	-0.241	-0.219	-0.664	-2.190
220	-0.197	-0.242	-0.220	-0.667	-2.200
221	-0.197	-0.243	-0.221	-0.670	-2.210
222	-0.198	-0.243	-0.222	-0.673	-2.220
223	-0.198	-0.244	-0.223	-0.676	-2.230
224	-0.199	-0.245	-0.224	-0.679	-2.240
225	-0.199	-0.246	-0.225	-0.682	-2.250
226	-0.200	-0.247	-0.226	-0.685	-2.260
227	-0.200	-0.248	-0.227	-0.688	-2.270
228	-0.201	-0.249	-0.228	-0.691	-2.280
229	-0.201	-0.250	-0.229	-0.694	-2.290
230	-0.202	-0.251	-0.230	-0.697	-2.300
231	-0.202	-0.252	-0.231	-0.700	-2.310
232	-0.203	-0.253	-0.232	-0.703	-2.320
233	-0.203	-0.254	-0.233	-0.706	-2.330
234	-0.204	-0.254	-0.234	-0.709	-2.340
235	-0.204	-0.255	-0.235	-0.712	-2.350
236	-0.205	-0.256	-0.236	-0.715	-2.360
237	-0.205	-0.257	-0.237	-0.718	-2.370
238	-0.206	-0.258	-0.238	-0.721	-2.380
239	-0.206	-0.259	-0.239	-0.724	-2.390
240	-0.207	-0.260	-0.240	-0.727	-2.400
241	-0.207	-0.261	-0.241	-0.730	-2.410
242	-0.208	-0.262	-0.242	-0.733	-2.420
243	-0.208	-0.263	-0.243	-0.736	-2.430
244	-0.209	-0.264	-0.244	-0.739	-2.440
245	-0.209	-0.265	-0.245	-0.742	-2.450
246	-0.210	-0.266	-0.246	-0.745	-2.460
247	-0.210	-0.266	-0.247	-0.748	-2.470
248	-0.211	-0.267	-0.248	-0.752	-2.480
249	-0.211	-0.268	-0.249	-0.755	-2.490
250	-0.212	-0.269	-0.250	-0.758	-2.500


Direct/Refraction/Reflection Curves Vp1=1000 Vp2=2000 H=50
0.000
-0.050
-0.100
-0.150
-0.200
-0.250
-0.300
Time (s)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
Refractions (s)
Reflection (s)
Direct (s)
Offset (m)

Appendix 4A

Water Chemistry Analysis Results

Water Quality Report

Environment Canterbury
Your regional council

Print Date:	7/05/2008			
Sample No:	**2708162**		Collection Date:	**12/12/2007**
Site ID:	**WTK000834**	Well No: **I38/0053**	Collection Time:	**1430**
Owner:	**GRAYHILLS PARTNERSHIP**		Cost Code	026112
Location:	**TEKAPO**		Project ID:	
Well Depth:	8.9		Sampler:	Kirsty
Well Use:	Domestic and Stockwater		Lab. Batch No.	2701641
Well Use:			Approved By:	SUEST
Well Use:			Approved On:	28/03/2008

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	111	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	0.018	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.10	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.14	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	18	mg/L	Dissolved APHA 3111 B	Chch
Chloride	3	mg/L	APHA 4500-Cl E Autoanalyser	Chch
Conductivity	20	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.031	mg/L	APHA 4500-P B,F	Chch
Fluoride	0.12	mg/L	*APHA 4110B	ıch-CIN
Ion balance	-4.7	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	6.7	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.17	mg/L	APHA 4500-NO3 F	Chch
Oxygen 18	-11.86	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	7.1		APHA 4500-H B Meter	Chch
Potassium dissolved	1.3	mg/L	APHA 3111 B	Chch
Reactive Silica	14	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	12	mg/L	APHA 3111 B	Chch
Sulphate	8.0	mg/L	*APHA 4110 B	ıch-CIN
Sum of anions	2.205	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	2.007	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	73	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	21.3	mS/m	NI-YSI 63 Meter	Field
Depth to Water	1.40	m	NI-Field Measurement	Field
Dissolved Oxygen	4.85	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	42.9	%	NI-YSI/550 DO Meter	Field
pH field	6.8		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	60	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

'<' means that the parameter was not detected at the detection limit shown
'>' means that the bacterial count was greater than the value shown

Water Quality Report Continued

Sample No:	**2708162**			Collection Date:	**12/12/2007**
Site ID:	**WTK000834**	Well No:	**I38/0053**	Collection Time:	**1430**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.8	°C	NI-YSI/550 DO Meter	Field
Well Head Security	non-secure w		NI-Field observations	Field
Well Surroundings	protected by s		NI-Field observations	Field

'<' means that the parameter was not detected at the detection limit shown
'>' means that the bacterial count was greater than the value shown

Water Quality Report

Print Date: 7/05/2008

Environment Canterbury
Your regional council

Sample No:	**2707107**	Collection Date:	**8/10/2007**
Site ID:	**WTK000874** Well No: **H38/0057**	Collection Time:	**0730**
Owner:	**Mr S Lancaster**	Cost Code	026112
Location:	**TWIZEL**	Project ID:	
Well Depth:	66	Sampler:	Frank Hocken
Well Use:	Domestic and Stockwater	Lab. Batch No.	2701704
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	25/10/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	38	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Alkalinity to pH 4,5	31	mg CaCO3/	APHA 2320 B Titration to pH 4.5	Chch
Aluminium	<0.006	mg/L	*APHA 3120B ICP-OES	ıch-CIN
Arsenic	<0.002	mg/L	APHA 3113 B acid soluble	Chch
Boron	<0.01	mg/L	*APHA 3120B ICP-OES	ıch-CIN
Calcium	6.3	mg/L	APHA 3111 B acid soluble	Chch
Chloride	0.3	mg/L	APHA 4110 B IC	Chch
Conductivity	6	mS/m	APHA 2510 B Meter	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Free CO2	5	mg/L	APHA 4500-CO2 D from pH & Alkalinity	Chch
Ion balance	-4.1	% diff	APHA 1030 F Calculation	Chch
Iron	<0.03	mg/L	APHA 3111 B acid soluble	Chch
Magnesium	1.6	mg/L	APHA 3111 B acid soluble	Chch
Manganese	<0.01	mg/L	APHA 3111 B acid soluble	Chch
Nitrate Nitrogen	0.1	mg/L	APHA 4110B IC	Chch
pH	7.1		APHA 4500-H B Meter	Chch
Potassium	0.5	mg/L	APHA 3111 B acid soluble	Chch
Reactive Silica	15	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium	3.3	mg/L	APHA 3111 B acid soluble	Chch
Sulphate	0.7	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.653	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.601	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	22	mg CaCO3/	APHA 2340B Calculation	Chch
Turbidity	0.4	NTU	APHA 2130 B Meter	Chch
Microbiological Analyses				
E coli	<1	MPN/100mL	APHA 9223 Colilert Kit	Chch
Total Coliforms	<1	MPN/100mL	APHA 9223 Colilert Kit	Chch

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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007			
Sample No:	**2706883**		Collection Date:	**1/10/2007**
Site ID:	**WTK000835**	Well No: **I39/0007**	Collection Time:	**1045**
Owner:	**HALDON STATION LTD**		Cost Code	026112
Location:	**TEKAPO**		Project ID:	
Well Depth:	18		Sampler:	Kirsty/Phil
Well Use:	Domestic Supply		Lab. Batch No.	2701641
Well Use:	Domestic Supply		Approved By:	SUEST
Well Use:			Approved On:	14/11/2007
Comments:				

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	56	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.009	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	12	mg/L	Dissolved APHA 3111 B	Chch
Chloride	1.6	mg/L	APHA 4110 B IC	Chch
Conductivity	10	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.013	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.1	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	1.2	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.3	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.32	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	7.3		APHA 4500-H B Meter	Chch
Potassium dissolved	0.9	mg/L	APHA 3111 B	Chch
Reactive Silica	13	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	5.7	mg/L	APHA 3111 B	Chch
Sulphate	3.2	mg/L	APHA 4110 B IC	Chch
Sum of anions	1.052	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.969	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	35	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	10.7	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-1.50	m	NI-Field Measurement	Field
Dissolved Oxygen	5.65	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	50.60	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	7.2		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	1.0	L/s	NI-Field Measurement	Field
Purging Time	20	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No: **2706883** Collection Date: **1/10/2007**
Site ID: **WTK000835** Well No: **I39/0007** Collection Time: **1045**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.5	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by bo		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
Your regional council

Print Date: 20/11/2007

Sample No:	**2706884**			Collection Date:	**1/10/2007**
Site ID:	**WTK000833**	Well No:	**I38/0003**	Collection Time:	**1200**
Owner:	**McKAY, P & A**			Cost Code	026112
Location:	**BURKES PASS**			Project ID:	
Well Depth:	48			Sampler:	Kirsty/Phil
Well Use:				Lab. Batch No.	2701641
Well Use:				Approved By:	SUEST
Well Use:				Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	69	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	0.036	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.009	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	13	mg/L	Dissolved APHA 3111 B	Chch
Chloride	4.2	mg/L	APHA 4110 B IC	Chch
Conductivity	16	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.014	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-3.4	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	5.6	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	1.6	mg/L	APHA 4110B IC	Chch
Oxygen 18	-12.37	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	6.9		APHA 4500-H B Meter	Chch
Potassium dissolved	0.9	mg/L	APHA 3111 B	Chch
Reactive Silica	13	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	8.2	mg/L	APHA 3111 B	Chch
Sulphate	11	mg/L	APHA 4110 B IC	Chch
Sum of anions	1.593	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	1.487	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	56	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	16.7	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-5.33	m	NI-Field Measurement	Field
Dissolved Oxygen	10.4	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	93.4	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	6.7		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.15	L/s	NI-Field Measurement	Field
Purging Time	120	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706884**			Collection Date:	**1/10/2007**
Site ID:	**WTK000833**	Well No:	**I38/0003**	Collection Time:	**1200**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.2	°C	NI-YSI/550 DO Meter	Field
Well Head Security	no well cap		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Water Quality Report

Print Date:	20/11/2007		
Sample No:	**2706885**	Collection Date:	**1/10/2007**
Site ID:	**WTK000832** Well No: **I38/0052**	Collection Time:	**1330**
Owner:	**GLEN ROCK STN LTD**	Cost Code	026112
Location:	**TEKAPO**	Project ID:	
Well Depth:	2	Sampler:	Kirsty/Phil
Well Use:	Domestic Supply	Lab. Batch No.	2701641
Well Use:	Stock Supply	Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	39	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	0.014	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.008	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	5.3	mg/L	Dissolved APHA 3111 B	Chch
Chloride	1.8	mg/L	APHA 4110 B IC	Chch
Conductivity	7	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.010	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-3.2	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	2.1	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.15	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	6.7		APHA 4500-H B Meter	Chch
Potassium dissolved	0.4	mg/L	APHA 3111 B	Chch
Reactive Silica	12	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	5.2	mg/L	APHA 3111 B	Chch
Sulphate	1.0	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.718	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.673	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	22	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	7.3	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-0.59	m	NI-Field Measurement	Field
Dissolved Oxygen	7.7	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	64.7	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	6.5		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	1.0	L/s	NI-Field Measurement	Field
Purging Time	7	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	pressure tank		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706885**	Collection Date:	**1/10/2007**
Site ID:	**WTK000832** Well No: **I38/0052**	Collection Time:	**1330**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	7.6	°C	NI-YSI/550 DO Meter	Field
Well Head Security	no well cap		NI-Field observations	Field
Well Surroundings	covered by sh		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007		
Sample No:	**2706886**	Collection Date:	**1/10/2007**
Site ID:	**WTK000836** Well No: **I39/0004**	Collection Time:	**1615**
Owner:	**HALDON STATION LTD**	Cost Code	026112
Location:	**Totara Peak**	Project ID:	
Well Depth:	68	Sampler:	Kirsty/Phil
Well Use:	Irrigation	Lab. Batch No.	2701641
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	69	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.011	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	16	mg/L	Dissolved APHA 3111 B	Chch
Chloride	1.4	mg/L	APHA 4110 B IC	Chch
Conductivity	12	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.016	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-2.4	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	1.1	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.4	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.29	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	8.1		APHA 4500-H B Meter	Chch
Potassium dissolved	1.1	mg/L	APHA 3111 B	Chch
Reactive Silica	13	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	7.0	mg/L	APHA 3111 B	Chch
Sulphate	3.9	mg/L	APHA 4110 B IC	Chch
Sum of anions	1.281	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	1.222	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	44	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	13.0	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-5.9	m	NI-Field Measurement	Field
Dissolved Oxygen	3.97	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	37.9	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.4		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	300	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706886**			Collection Date:	**1/10/2007**
Site ID:	**WTK000836**	Well No:	**I39/0004**	Collection Time:	**1615**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	13.2	°C	NI-YSI/550 DO Meter	Field
Well Head Security	non-secure w		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007			
Sample No:	**2706887**		Collection Date:	**1/10/2007**
Site ID:	**WTK000866**	Well No: **I38/0004**	Collection Time:	**1700**
Owner:	**MACKAY, PW**		Cost Code	026112
Location:	**TEKAPO**		Project ID:	
Well Depth:	28		Sampler:	Kirsty/Phil
Well Use:	Domestic and Stockwater		Lab. Batch No.	2701641
Well Use:			Approved By:	SUEST
Well Use:			Approved On:	14/11/2007
Comments:				

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	145	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.009	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.64	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	8.5	mg/L	Dissolved APHA 3111 B	Chch
Chloride	4.0	mg/L	APHA 4110 B IC	Chch
Conductivity	30	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.008	mg/L	APHA 4500-P B,F	Chch
Fluoride	1.1	mg/L	APHA 4110 B IC	Chch
Ion balance	-2.6	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	1.9	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.86	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	8.3		APHA 4500-H B Meter	Chch
Potassium dissolved	1.4	mg/L	APHA 3111 B	Chch
Reactive Silica	12	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	55	mg/L	APHA 3111 B	Chch
Sulphate	31	mg/L	APHA 4110 B IC	Chch
Sum of anions	3.143	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	2.984	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	29	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	31.5	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-0.6	m	NI-Field Measurement	Field
Dissolved Oxygen	0.30	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	2.60	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.5		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.20	L/s	NI-Field Measurement	Field
Purging Time	120	min	NI-Field Measurement	Field
Sample Appearance	slightly turbid		NI-Field observations	Field
Sample Colour	reddish		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706887**			Collection Date:	**1/10/2007**
Site ID:	**WTK000866**	Well No:	**I38/0004**	Collection Time:	**1700**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.5	°C	NI-YSI/550 DO Meter	Field
Well Head Security	non-secure w		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007			
Sample No:	**2706888**		Collection Date:	**2/10/2007**
Site ID:	**WTK000864**	Well No: **H38/0059**	Collection Time:	**1100**
Owner:	**RUATANAWHIA FARM LIMITED**		Cost Code	026112
Location:	**TWIZEL**		Project ID:	
Well Depth:	53		Sampler:	Kirsty/Phil
Well Use:	Domestic and Stockwater		Lab. Batch No.	2701641
Well Use:			Approved By:	SUEST
Well Use:			Approved On:	14/11/2007
Comments:				

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	63	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.022	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	0.016	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	12	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.6	mg/L	APHA 4110 B IC	Chch
Conductivity	10	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.027	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-5.5	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	0.07	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	1.3	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-10.94	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	8.4		APHA 4500-H B Meter	Chch
Potassium dissolved	0.7	mg/L	APHA 3111 B	Chch
Reactive Silica	13	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	6.0	mg/L	APHA 3111 B	Chch
Sulphate	2.1	mg/L	APHA 4110 B IC	Chch
Sum of anions	1.101	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.987	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	35	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	10.6	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-10.50	m	NI-Field Measurement	Field
Dissolved Oxygen	0.1	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	0.8	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.7		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.20	L/s	NI-Field Measurement	Field
Purging Time	180	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

'<' means that the parameter was not detected at the detection limit shown
'>' means that the bacterial count was greater than the value shown

Water Quality Report Continued

Sample No:	**2706888**			Collection Date:	**2/10/2007**
Site ID:	**WTK000864**	Well No:	**H38/0059**	Collection Time:	**1100**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	11.2	°C	NI-YSI/550 DO Meter	Field
Well Head Security	non-secure w		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Water Quality Report

Print Date: 20/11/2007

Sample No:	**2706889**	Collection Date:	**2/10/2007**
Site ID:	**WTK000841** Well No: **H38/0025**	Collection Time:	**1300**
Owner:	**SHEARER AL**	Cost Code	026112
Location:	**TWIZEL**	Project ID:	
Well Depth:	4.5	Sampler:	Kirsty/Phil
Well Use:	Domestic and Stockwater	Lab. Batch No.	2701641
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	13	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.009	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	2.8	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.4	mg/L	APHA 4110 B IC	Chch
Conductivity	3	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.006	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-0.19	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	0.3	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.26	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	6.4		APHA 4500-H B Meter	Chch
Potassium dissolved	0.3	mg/L	APHA 3111 B	Chch
Reactive Silica	8.4	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	1.9	mg/L	APHA 3111 B	Chch
Sulphate	1.2	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.257	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.256	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	8	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	3.0	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-1.2	m	NI-Field Measurement	Field
Dissolved Oxygen	7.49	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	64.2	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	6.1		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.30	L/s	NI-Field Measurement	Field
Purging Time	5	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sampling Point	outside tap		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706889**			Collection Date:	**2/10/2007**
Site ID:	**WTK000841**	Well No:	**H38/0025**	Collection Time:	**1300**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Water Temperature	8.6	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by sh		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007			
Sample No:	**2706890**		Collection Date:	**2/10/2007**
Site ID:	**WTK000843**	Well No: **H38/0051**	Collection Time:	**1320**
Owner:	**MR M A CAIN**		Cost Code	026112
Location:	**TWIZEL**		Project ID:	
Well Depth:	41		Sampler:	Kirsty/Phil
Well Use:	Domestic Supply		Lab. Batch No.	2701641
Well Use:			Approved By:	SUEST
Well Use:			Approved On:	14/11/2007
Comments:				

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	45	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.014	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	11	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.4	mg/L	APHA 4110 B IC	Chch
Conductivity	8	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.010	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-6.8	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	0.8	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-9.68	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	8.1		APHA 4500-H B Meter	Chch
Potassium dissolved	0.7	mg/L	APHA 3111 B	Chch
Reactive Silica	12	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	2.6	mg/L	APHA 3111 B	Chch
Sulphate	4.9	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.858	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.748	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	31	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	8.4	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-28.5	m	NI-Field Measurement	Field
Dissolved Oxygen	7.00	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	63.6	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.6		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	1.5	L/s	NI-Field Measurement	Field
Purging Time	10	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706890**	Collection Date:	**2/10/2007**
Site ID:	**WTK000843** Well No: **H38/0051**	Collection Time:	**1320**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	11	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007			
Sample No:	**2706891**		Collection Date:	**2/10/2007**
Site ID:	**WTK000837**	Well No: **H38/0021**	Collection Time:	**N/R**
Owner:	**LYON N**		Cost Code	026112
Location:	**TWIZEL**		Project ID:	
Well Depth:	12.2		Sampler:	Kirsty/Phil
Well Use:	Domestic Supply		Lab. Batch No.	2701641
Well Use:			Approved By:	SUEST
Well Use:			Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	15	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.017	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	3.4	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.5	mg/L	APHA 4110 B IC	Chch
Conductivity	3	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.006	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-1.6	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	0.06	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	0.4	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.27	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	6.8		APHA 4500-H B Meter	Chch
Potassium dissolved	0.3	mg/L	APHA 3111 B	Chch
Reactive Silica	7.9	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	1.6	mg/L	APHA 3111 B	Chch
Sulphate	1.2	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.292	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.283	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	10	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	3.1	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-2.08	m	NI-Field Measurement	Field
Dissolved Oxygen	10.21	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	87.0	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	6.6		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	5	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	pressure tank		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706891**			Collection Date:	**2/10/2007**
Site ID:	**WTK000837**	Well No:	**H38/0021**	Collection Time:	**N/R**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	hose		NI-Field observations	Field
Water Temperature	8.2	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by sh		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
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Print Date:	20/11/2007		
Sample No:	**2706892**	Collection Date:	**2/10/2007**
Site ID:	**WTK000865** Well No: **H38/0063**	Collection Time:	**1430**
Owner:	**MR A P RANSON (PUKAKI DOWNS)**	Cost Code	026112
Location:	**TWIZEL**	Project ID:	
Well Depth:	48	Sampler:	Kirsty/Phil
Well Use:	Domestic Supply	Lab. Batch No.	2701641
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	42	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.009	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	5.5	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.8	mg/L	APHA 4110 B IC	Chch
Conductivity	7	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.032	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.7	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	2.2	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-10.86	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	7.9		APHA 4500-H B Meter	Chch
Potassium dissolved	0.5	mg/L	APHA 3111 B	Chch
Reactive Silica	18	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	4.5	mg/L	APHA 3111 B	Chch
Sulphate	0.5	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.729	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.664	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	23	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	7.0	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-14.85	m	NI-Field Measurement	Field
Dissolved Oxygen	2.97	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	26.6	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.1		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field
Sampling Point	pump		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706892**			Collection Date:	**2/10/2007**
Site ID:	**WTK000865**	Well No:	**H38/0063**	Collection Time:	**1430**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Water Temperature	10.4	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by sh		NI-Field observations	Field

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Water Quality Report

Environment Canterbury
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Print Date:	20/11/2007		
Sample No:	**2706893**	Collection Date:	**2/10/2007**
Site ID:	**WTK000863** Well No: **H38/0038**	Collection Time:	**1600**
Owner:	**MR R J HOUSTON**	Cost Code	026112
Location:	**PUKAKI DOWNS**	Project ID:	
Well Depth:	36.2	Sampler:	Kirsty/Phil
Well Use:	Domestic Supply	Lab. Batch No.	2701641
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	52	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.015	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	8.1	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.9	mg/L	APHA 4110 B IC	Chch
Conductivity	9	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.010	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.2	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	2.7	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.5	mg/L	APHA 4110B IC	Chch
Oxygen 18	-10.85	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	7.4		APHA 4500-H B Meter	Chch
Potassium dissolved	0.7	mg/L	APHA 3111 B	Chch
Reactive Silica	17	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	4.9	mg/L	APHA 3111 B	Chch
Sulphate	0.9	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.933	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.857	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	31	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	9.0	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-23.2	m	NI-Field Measurement	Field
Dissolved Oxygen	3.57	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	32.1	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	7.2		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	30	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706893**			Collection Date:	**2/10/2007**
Site ID:	**WTK000863**	Well No:	**H38/0038**	Collection Time:	**1600**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.5	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by sh		NI-Field observations	Field

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Water Quality Report

Print Date:	20/11/2007				
Sample No:	**2706894**			Collection Date:	**2/10/2007**
Site ID:	**WTK000838**	Well No:	**I38/0015**	Collection Time:	**1845**
Owner:	**MR D A FASTIER**			Cost Code	026112
Location:	**LAKE TEKAPO**			Project ID:	
Well Depth:	80.8			Sampler:	Kirsty/Phil
Well Use:	Domestic and Stockwater			Lab. Batch No.	2701641
Well Use:	Irrigation			Approved By:	SUEST
Well Use:				Approved On:	14/11/2007
Comments:					

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	96	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	0.047	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.18	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	18	mg/L	Dissolved APHA 3111 B	Chch
Chloride	1.6	mg/L	APHA 4110 B IC	Chch
Conductivity	16	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.008	mg/L	APHA 4500-P B,F	Chch
Fluoride	0.5	mg/L	APHA 4110 B IC	Chch
Ion balance	-2.9	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	3.2	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.3	mg/L	APHA 4110B IC	Chch
Oxygen 18	-12.13	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	8.0		APHA 4500-H B Meter	Chch
Potassium dissolved	0.6	mg/L	APHA 3111 B	Chch
Reactive Silica	14	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	10.0	mg/L	APHA 3111 B	Chch
Sulphate	3.7	mg/L	APHA 4110 B IC	Chch
Sum of anions	1.718	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	1.622	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	58	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	16.9	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-11.03	m	NI-Field Measurement	Field
Dissolved Oxygen	2.87	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	29.80	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.2		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	540	min	NI-Field Measurement	Field
Sample Appearance	turbid		NI-Field observations	Field
Sample Colour	yellow/grey		NI-Field observations	Field
Sample Odour	"rotten" smell		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706894**			Collection Date:	**2/10/2007**
Site ID:	**WTK000838**	Well No:	**I38/0015**	Collection Time:	**1845**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.8	°C	NI-YSI/550 DO Meter	Field
Well Head Security	non-secure w		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

'<' means that the parameter was not detected at the detection limit shown
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Water Quality Report

Environment Canterbury
Your regional council

Print Date:	20/11/2007				
Sample No:	**2706895**			Collection Date:	**2/10/2007**
Site ID:	**WTK000867**	Well No:	**I38/0014**	Collection Time:	**1730**
Owner:	**MR D A FASTIER**			Cost Code	026112
Location:	**LAKE TEKAPO**			Project ID:	
Well Depth:	23.95			Sampler:	Kirsty/Phil
Well Use:	Domestic and Stockwater			Lab. Batch No.	2701641
Well Use:	Irrigation			Approved By:	SUEST
Well Use:				Approved On:	14/11/2007
Comments:					

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	114	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.022	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.02	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	16	mg/L	Dissolved APHA 3111 B	Chch
Chloride	2.5	mg/L	APHA 4110 B IC	Chch
Conductivity	19	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.004	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.4	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	7.1	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.6	mg/L	APHA 4110B IC	Chch
Oxygen 18	-11.08	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	7.5		APHA 4500-H B Meter	Chch
Potassium dissolved	0.8	mg/L	APHA 3111 B	Chch
Reactive Silica	17	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	11	mg/L	APHA 3111 B	Chch
Sulphate	3.3	mg/L	APHA 4110 B IC	Chch
Sum of anions	2.052	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	1.879	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	69	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	19.8	mS/m	NI-YSI 63 Meter	Field
Depth to Water	-5.05	m	NI-Field Measurement	Field
Dissolved Oxygen	4.94	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	44.3	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	7.2		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	30	min	NI-Field Measurement	Field
Sample Appearance	very aerated		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	2706895			Collection Date:	2/10/2007
Site ID:	WTK000867	Well No:	I38/0014	Collection Time:	1730

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.3	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by bo		NI-Field observations	Field

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Water Quality Report

Print Date: 20/11/2007

Environment Canterbury
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Sample No:	**2706896**	Collection Date:	**3/10/2007**
Site ID:	**WTK000862** Well No: **I37/0013**	Collection Time:	**1145**
Owner:	**UNIVERSITY OF CANTERBURY**	Cost Code	026112
Location:	**Tekapo**	Project ID:	
Well Depth:	22	Sampler:	Kirsty/Phil
Well Use:	Domestic Supply	Lab. Batch No.	2701641
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments: Sampled from artesian flow

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	122	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.023	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	32	mg/L	Dissolved APHA 3111 B	Chch
Chloride	1.3	mg/L	APHA 4110 B IC	Chch
Conductivity	23	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.003	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.1	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	3.7	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.3	mg/L	APHA 4110B IC	Chch
Oxygen 18	-12.48	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	8.0		APHA 4500-H B Meter	Chch
Potassium dissolved	0.7	mg/L	APHA 3111 B	Chch
Reactive Silica	11	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	7.4	mg/L	APHA 3111 B	Chch
Sulphate	18	mg/L	APHA 4110 B IC	Chch
Sum of anions	2.433	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	2.243	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	95	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	23.8	mS/m	NI-YSI 63 Meter	Field
Depth to Water	0.95	m	NI-Field Measurement	Field
Dissolved Oxygen	2.08	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	18.5	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	8.1		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.50	L/s	NI-Field Measurement	Field
Purging Time	artesian	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706896**			Collection Date:	**3/10/2007**
Site ID:	**WTK000862**	Well No:	**I37/0013**	Collection Time:	**1145**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Sampling Point	hose		NI-Field observations	Field
Water Temperature	9.8	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Water Quality Report

Print Date: 20/11/2007

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Sample No:	**2706897**	Collection Date:	**3/10/2007**
Site ID:	**WTK000840** Well No: **I37/0009**	Collection Time:	**N/R**
Owner:	**MACKENZIE DISTRICT COUNCIL**	Cost Code	026112
Location:	**TEKAPO**	Project ID:	
Well Depth:	6	Sampler:	Kirsty/Phil
Well Use:	Public Water Supply	Lab. Batch No.	2701641
Well Use:		Approved By:	SUEST
Well Use:		Approved On:	14/11/2007

Comments: Sampled from gallery manhole

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	96	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	0.021	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.019	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	16	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.3	mg/L	APHA 4110 B IC	Chch
Conductivity	16	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.002	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.4	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	<0.1	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.4	mg/L	APHA 4110B IC	Chch
Oxygen 18	-10.54	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	9.1		APHA 4500-H B Meter	Chch
Potassium dissolved	13	mg/L	APHA 3111 B	Chch
Reactive Silica	8.5	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	9.4	mg/L	APHA 3111 B	Chch
Sulphate	4.0	mg/L	APHA 4110 B IC	Chch
Sum of anions	1.695	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	1.553	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	40	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	17.0	mS/m	NI-YSI 63 Meter	Field
Dissolved Oxygen	9.3	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	75.5	%	NI-YSI/550 DO Meter	Field
DO meter number	D9		NI-YSI/550 DO Meter	Field
pH field	9.5		NI-YSI 63 Meter	Field
pH/salinity meter no	PC5		NI-YSI 63 Meter	Field
Purging Rate	0.20	L/s	NI-Field Measurement	Field
Purging Time	10	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field
Sampling Point	pump		NI-Field observations	Field

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Water Quality Report Continued

Sample No:	**2706897**			Collection Date:	**3/10/2007**
Site ID:	**WTK000840**	Well No:	**I37/0009**	Collection Time:	**N/R**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Water Temperature	6.0	°C	NI-YSI/550 DO Meter	Field
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	covered by bo		NI-Field observations	Field

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Water Quality Report

Print Date: 20/11/2007

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Sample No:	**2706900**	Collection Date:	**2/10/2007**
Site ID:	**WTK000870**	Collection Time:	**1700**
Source:	**Lake Pukaki**	Cost Code	026112
Description:	**South of spillway in canal (left bank)**	Project ID:	
Sampler:	Kirsty/Phil	Lab. Batch No.	2701641
Comments:		Approved By:	SUEST
		Approved On:	14/11/2007

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	29	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	0.030	mg/L	*Dissolved APHA 3120B ICP-OES	ch-CIN
Ammonia Nitrogen	0.11	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ch-CIN
Calcium dissolved	8.5	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.4	mg/L	APHA 4110 B IC	Chch
Conductivity	6	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.020	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.3	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	0.5	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-9.83	o/oo	* NI With respect to VSMOW	s-Chch
pH	7.7		APHA 4500-H B Meter	Chch
Potassium dissolved	0.6	mg/L	APHA 3111 B	Chch
Reactive Silica	3.6	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	1.4	mg/L	APHA 3111 B	Chch
Sulphate	5.1	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.600	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.551	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	23	mg CaCO3/L	APHA 2340B - Calculation	Chch

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Water Quality Report

Print Date: 20/11/2007

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Sample No:	**2706901**	Collection Date:	**2/10/2007**
Site ID:	**WTK000869**	Collection Time:	**1130**
Source:	**Lake Ohau**	Cost Code	026112
Description:	**East of spillway in canal (left bank)**	Project ID:	
Sampler:	Kirsty/Phil	Lab. Batch No.	2701641
Comments:		Approved By:	SUEST
		Approved On:	14/11/2007

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	31	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ch-CIN
Ammonia Nitrogen	0.012	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ch-CIN
Calcium dissolved	8.6	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.3	mg/L	APHA 4110 B IC	Chch
Conductivity	6	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	<0.001	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-5.5	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	0.6	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-9.56	o/oo	* NI With respect to VSMOW	s-Chch
pH	7.8		APHA 4500-H B Meter	Chch
Potassium dissolved	0.5	mg/L	APHA 3111 B	Chch
Reactive Silica	4.1	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	1.4	mg/L	APHA 3111 B	Chch
Sulphate	4.5	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.618	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.554	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	24	mg CaCO3/L	APHA 2340B - Calculation	Chch

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Water Quality Report

Environment Canterbury
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Print Date: 20/11/2007

Sample No:	**2706902**	Collection Date:	**3/10/2007**
Site ID:	**WTK000868**	Collection Time:	**1330**
Source:	**Lake Tekapo**	Cost Code	026112
Description:	**By Intake**	Project ID:	
Sampler:	Kirsty/Phil	Lab. Batch No.	2701641
Comments:		Approved By:	SUEST
		Approved On:	14/11/2007

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	26	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.006	mg/L	*Dissolved APHA 3120B ICP-OES	ch-CIN
Ammonia Nitrogen	0.018	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	<0.01	mg/L	*Dissolved APHA 3120B ICP-OES	ch-CIN
Calcium dissolved	7.3	mg/L	Dissolved APHA 3111 B	Chch
Chloride	0.3	mg/L	APHA 4110 B IC	Chch
Conductivity	5	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.001	mg/L	APHA 4500-P B,F	Chch
Fluoride	<0.2	mg/L	APHA 4110 B IC	Chch
Ion balance	-4.8	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	0.5	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	<0.1	mg/L	APHA 4110B IC	Chch
Oxygen 18	-9.89	o/oo	* NI With respect to VSMOW	s-Chch
pH	7.7		APHA 4500-H B Meter	Chch
Potassium dissolved	0.4	mg/L	APHA 3111 B	Chch
Reactive Silica	4.0	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	1.4	mg/L	APHA 3111 B	Chch
Sulphate	4.1	mg/L	APHA 4110 B IC	Chch
Sum of anions	0.527	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.479	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	20	mg CaCO3/L	APHA 2340B - Calculation	Chch

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Water Quality Report

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Print Date:	7/05/2008			
Sample No:	**2708164**		Collection Date:	**12/12/2007**
Site ID:	**WTK000875**	Well No: **H38/0188**	Collection Time:	**1130**
Owner:	**Andrew Eccleshall & Claire Le Grice**		Cost Code	026112
Location:	**LAKE OHAU**		Project ID:	
Well Depth:	36		Sampler:	Kirsty
Well Use:	Domestic Supply		Lab. Batch No.	2701641
Well Use:			Approved By:	SUEST
Well Use:			Approved On:	28/03/2008

Comments:

PARAMETER	RESULT	UNITS	METHOD	LAB
Chemical Analyses				
Alkalinity to pH 4,5	39	mg HCO3/L	APHA 2320 B Titration to pH 4.5	Chch
Aluminium dissolved	<0.005	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Ammonia Nitrogen	0.013	mg/L	APHA 4500-NH3 F	Chch
Arsenic dissolved	<0.002	mg/L	Dissolved APHA 3113 B GFAA	Chch
Boron dissolved	0.06	mg/L	*Dissolved APHA 3120B ICP-OES	ıch-CIN
Calcium dissolved	6.4	mg/L	Dissolved APHA 3111 B	Chch
Chloride	<1	mg/L	APHA 4500-Cl E Autoanalyser	Chch
Conductivity	6	mS/m	APHA 2510 B Meter	Chch
Dissolved Reactive Phosphorus	0.004	mg/L	APHA 4500-P B,F	Chch
Fluoride	0.074	mg/L	*APHA 4110B	ıch-CIN
Ion balance	-3.9	% diff	APHA 1030 F Calculation	Chch
Iron dissolved	<0.03	mg/L	Dissolved APHA 3111 B	Chch
Magnesium dissolved	1.5	mg/L	APHA 3111 B	Chch
Manganese dissolved	<0.01	mg/L	Dissolved APHA 3111 B	Chch
Nitrate Nitrogen	0.25	mg/L	APHA 4500-NO3 F	Chch
Oxygen 18	-10.68	o/oo	* NI With respect to VSMOW	ıs-Chch
pH	7.7		APHA 4500-H B Meter	Chch
Potassium dissolved	0.5	mg/L	APHA 3111 B	Chch
Reactive Silica	13	mg SiO2/L	APHA 4500-Si E modified	Chch
Sodium dissolved	3.5	mg/L	APHA 3111 B	Chch
Sulphate	0.6	mg/L	*APHA 4110 B	ıch-CIN
Sum of anions	0.659	meq/L	APHA 1030 F Calculation	Chch
Sum of cations	0.609	meq/L	APHA 1030 F Calculation	Chch
Total Hardness	22	mg CaCO3/	APHA 2340B - Calculation	Chch
Field Observations				
Conductivity field	6.7	mS/m	NI-YSI 63 Meter	Field
Dissolved Oxygen	7.60	mg/L	NI-YSI/550 DO Meter	Field
Dissolved Oxygen Saturation	68.1	%	NI-YSI/550 DO Meter	Field
pH field	7.7		NI-YSI 63 Meter	Field
Purging Time	60	min	NI-Field Measurement	Field
Sample Appearance	clear		NI-Field observations	Field
Sample Colour	colourless		NI-Field observations	Field
Sample Odour	odourless		NI-Field observations	Field
Sample Point Sterilised	not sterilised		NI-Field observations	Field
Sample Source	direct off well		NI-Field observations	Field
Sampling Point	pump		NI-Field observations	Field
Water Temperature	10.3	°C	NI-YSI/550 DO Meter	Field

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'>' means that the bacterial count was greater than the value shown

Water Quality Report Continued

Sample No:	**2708164**			Collection Date:	**12/12/2007**
Site ID:	**WTK000875**	Well No:	**H38/0188**	Collection Time:	**1130**

PARAMETER	RESULT	UNITS	METHOD	LAB
Field Observations				
Well Head Security	secure well ca		NI-Field observations	Field
Well Surroundings	uncovered		NI-Field observations	Field

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Appendix 4B

Tables 4.3 to 4.5

and

Figures 4.6 to 4.17

Table 4.1: Results of chemistry samples collected February 2005 by Environment Canterbury.

FEBRUARY 2005	Tekapo sub-basin						Twizel sub-basin							
Well Number	**I37/0009**	**I38/0003**	**I38/0015**	**I38/0052**	**I38/0053**	**I38/0054**	**H38/0004**	**H38/0021**	**H38/0025**	**H38/0032**	**H38/0035**	**H38/0051**	**I39/0004**	**I39/0007**
Well Depth (m)	6	48	80.8	4	13	6	11.4	12.2	4.03	2.85	113.4	41	68	18
Depth to Water (m)	Nm	-6.45	-10.65	-0.65	-0.3	nm	-3.6	-1.78	-1.9	-1.95	nm	nm	-5.55	nm
pH*	6.9	6.8	7.9	7.0	6.8	7.3	6.3	6.8	6.0	6.5	8.0	7.4	8.5	7.1
Water Temperature (°C)*	13.5	13.9	11.0	13.1	13.9	12.6	13.4	13.5	12.8	13.1	13.2	13.5	12.9	13.9
Conductivity at 25°C (mS/m)*	7.0	16.6	10.6	7.3	20.7	12.8	3.3	18.7	3.8	3.8	6.2	9.0	9.7	11.7
Dissolved Oxygen (mg/L)*	3.8	3.4	1.2	5.9	1.9	7.8	7.3	6.7	4.3	3.8	4.4	6.5	0.1	40.0
Dissolved Oxygen (% saturation)*	39.0	32.4	0.13	57.0	19.7	74.5	69.1	65.1	40.5	38.2	61	64	1.2	37.7
Alkalinity (mg HCO3/L)	17	93	49	40	119	70	17	16	16	17	30	47	50	59
Ammonia Nitrogen (mg/L)	0.009	0.022	0.051	0.01	0.02	0.011	0.005	0.0025	0.0025	0.027	0.017	0.0025	0.031	0.006
Calcium (mg/L)	4.0	14.0	6.0	5.0	18.0	11.0	2.9	3.1	3.7	3.6	5.6	12.0	9.5	12.0
Chloride (mg/L)	0.3	1.7	1.8	1.8	2.0	1.8	0.4	0.3	0.5	0.7	0.4	0.4	1.5	1.7
Iron (mg/L)	0.015	0.17	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.37	0.015	0.015	0.015	0.015
Magnesium (mg/L)	0.5	6.3	2.7	2.3	7.2	4.2	0.6	0.4	0.5	0.4	0.8	0.9	1.1	1.3
Manganese (mg/L)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Nitrate Nitrogen (mg/L)	0.05	0.7	0.05	0.1	0.1	0.6	0.1	0.05	0.6	0.1	0.1	0.05	0.05	0.5
Potassium (mg/L)	0.4	1.1	0.6	0.5	1.4	1.0	0.5	0.4	0.4	0.5	0.7	0.7	1.0	1.1
Reactive Silica (mg SiO2/L)	7.0	14.0	0.2	14.0	15.0	16.0	10.0	9.4	9.8	8.9	14.0	13.0	0.4	14.0
Sodium (mg/L)	1.3	9.3	9.9	5.7	13.0	7.2	2.3	1.8	2.4	2.0	2.9	2.7	6.6	6.5
Sulphate (mg/L)	2.0	4.0	4.7	0.8	7.9	3.5	0.5	0.9	1.2	1.3	1.2	4.7	3.2	2.9
Total Hardness (mg CaCO3/L)**	12	61	26	22	75	45	10	9	11	11	17	34	28	35
Total Dissolved Solids (mg/L)***	32	138	72	68	176	111	34	32	35	34	55	81	72	98
Sum of Anions (meq/L)	0.336	1.706	0.959	0.731	2.179	1.314	0.308	0.297	0.344	0.333	0.535	0.887	0.936	1.112
Sum of Cations (meq/L)	0.309	1.653	0.967	0.698	2.088	1.232	0.308	0.277	0.341	0.327	0.491	0.810	0.878	1.016
Ion Balance (% diff)	-4.2	-1.6	0.42	-2.3	-2.1	-3.2	0	-3.5	-0.44	-0.91	-4.3	-4.5	-3.2	-4.5
Sodium Absorption Ratio (meq/L)	0.90	1.03	0.52	0.53	1.18	0.96	0.53	0.66	0.68	0.73	0.90	1.94	1.09	1.36

Notes:

Aesthetic Effects - Exceeds 2005 New Zealand Drinking Water Standards (Ministry of Health, 2005) Maximum Acceptable Values

Health Effects - Exceeds 2005 New Zealand Drinking Water Standards (Ministry of Health, 2005) Maximum Acceptable Values

*	Parameters measured in the field
**	Total Hardness calculated as the sum of Calcium/0.4 and Magnesium/0.24
***	Total Dissolved Solids calculated by summing ion concentrations and reactive silica
nm	= not measured
<	= parameter not detected at the detection limit shown

Table 4.2: Results of chemistry samples collected in October 2007 for this study.

OCTOBER 2007	Tekapo sub-basin								
Well Number	**I37/0009**	**I37/0013**	**I38/0003**	**I38/0004**	**I38/0014**	**I38/0015**	**I38/0052**	**I38/0053**	**Lake Tekapo**
Sample Number	2706897	2706896	2706884	2706887	2706895	2706894	2706885	2708162	2706902
Well Depth (m)	6	22	48	28	23.95	80.8	2	8.9	0
Depth to Water (m)	nm	0.95	-5.33	-0.6	-5.05	-11.03	-0.59	-1.4	0
pH*	9.5	8.1	6.7	8.5	7.2	8.2	6.5	7.1	7.7
Water Temperature (°C)*	6.0	9.8	10.2	10.5	10.3	10.8	7.6	10.8	nm
Conductivity at 25°C (mS/m)*	17.0	23.8	16.7	31.5	19.8	16.9	7.3	21.3	5.0
Dissolved Oxygen (mg/L)*	9.3	2.08	10.4	0.3	4.94	2.87	7.7	4.85	nm
Dissolved Oxygen (% saturation)*	75.5	18.5	93.4	2.6	44.3	29.8	64.7	42.9	nm
Alkalinity (mg HCO_3/L)	96	122	69	145	114	96	39	111	26
Aluminium (mg/L)	0.021	<0.006	0.036	<0.006	<0.006	0.047	0.014	0.018	<0.006
Ammonia Nitrogen (mg/L)	0.019	0.023	0.009	0.009	0.022	0.18	0.008	0.1	0.018
Arsenic (mg/L)	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Boron (mg/L)	<0.01	<0.01	0.01	0.64	0.02	0.01	<0.01	0.14	<0.01
Calcium (mg/L)	16.0	32.0	13.0	8.5	16.0	18.0	5.3	18.0	7.3
Chloride (mg/L)	0.28	1.3	4.2	4.0	2.5	1.6	1.8	3.0	0.31
Fluoride (mg/L)	<0.2	<0.2	<0.2	1.1	<0.2	0.5	<0.2	0.12	<0.2
Iron (mg/L)	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Magnesium (mg/L)	<0.1	3.7	5.6	1.9	7.1	3.2	2.1	6.7	0.46
Manganese (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrate-Nitrogen (mg/L)	0.4	0.3	1.6	<0.1	0.6	0.3	0.1	0.17	<0.1
Potassium (mg/L)	13.0	0.7	0.9	1.4	0.8	0.6	0.4	1.3	0.5
Reactive Phosphorus (mg/L)	0.0022	0.0031	0.014	0.0075	0.0044	0.0082	0.0097	0.031	0.0011
Reactive Silica (mg SiO_2/L)	8.5	11.0	13.0	12.0	17.0	14.0	12.0	14.0	4.0
Sodium (mg/L)	9.4	7.4	8.2	55.0	11.0	10.0	5.2	12.0	1.4
Sulphate (mg/L)	4.0	18.0	11.0	31.0	3.3	3.7	1.0	8.0	4.1
Total Hardness (mg $CaCO_3$/L)**	40.0	95.0	56.0	29.0	69.0	58.0	22.0	73.0	20.0
Total Dissolved Solids (mg/L)***	148	196	127	260	172	148	67	174	44
Sum of Anions (meq/L)	1.69	2.43	1.59	3.13	2.05	1.72	0.72	2.08	0.52
Sum of Cations (meq/L)	1.54	2.24	1.49	3.01	1.88	1.61	0.67	2.00	0.47
Ion Balance (% diff)	-4.74	-4.10	-3.31	-2.05	-4.29	-3.12	-3.08	-1.90	-4.59
Sodium Absorption Ratio (meq/L)	0.65	0.33	0.48	4.44	0.58	0.57	0.48	0.61	0.14
Oxygen-18 (‰)	-10.54	-12.48	-12.37	-11.86	-11.08	-12.13	-11.15	-11.86	-9.89

OCTOBER 2007	Twizel sub-basin											
Well Number	**H38/0021**	**H38/0025**	**H38/0038**	**H38/0051**	**H38/0057**	**H38/0059**	**H38/0063**	**H38/0188**	**I39/0004**	**I39/0007**	**Lake Ohau**	**Lake Pukaki**
Sample Number	2706891	2706889	2706893	2706890	2707107	2706888	2706892	2708164	2706886	2706883	2706901	2706900
Well Depth (m)	12.2	4.5	36.2	41	66	53	48	36	68	18	0	0
Depth to Water (m)	-2.08	-1.2	-23.2	-28.5	nm	-10.5	-14.85	-6.25	-5.9	-1.5	0	0
pH*	6.6	6.1	7.2	8.6	7.1	8.7	8.1	7.7	8.4	7.2	7.8	7.7
Water Temperature (°C)*	8.2	8.6	10.5	11.0	nm	11.2	10.4	10.3	13.2	10.5	nm	nm
Conductivity at 25°C (mS/m)*	3.1	3.0	9.0	8.4	nm	10.6	7.0	6.7	13.0	10.7	6.0	6.0
Dissolved Oxygen (mg/L)*	10.21	7.49	3.57	7.0	nm	0.1	2.97	7.6	3.97	5.65	nm	nm
Dissolved Oxygen (% saturation)*	87.0	64.2	32.1	63.6	nm	0.8	26.6	68.1	37.9	50.6	nm	nm
Alkalinity (mg HCO_3/L)	15	13	52	45	38	63	42	39	69	56	31	29
Aluminium (mg/L)	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.005	<0.006	<0.006	<0.006	0.03
Ammonia Nitrogen (mg/L)	0.017	0.009	0.015	0.014	nm	0.022	0.009	0.013	0.011	0.009	0.012	0.11
Arsenic (mg/L)	<0.002	<0.002	<0.002	0.002	<0.002	0.016	<0.002	<0.002	<0.002	<0.002	0.002	<0.002
Boron (mg/L)	<0.01	<0.01	<0.001	<0.01	<0.01	0.01	<0.01	0.06	<0.01	<0.01	<0.01	<0.01
Calcium (mg/L)	3.4	2.8	8.1	11.0	6.3	12.0	5.5	6.4	16.0	12.0	8.6	8.5
Chloride (mg/L)	0.46	0.4	0.85	0.37	0.3	0.57	0.76	<1.0	1.4	1.6	0.34	0.37
Fluoride (mg/L)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.074	<0.2	<0.2	<0.2	<0.2
Iron (mg/L)	0.059	<0.03	<0.03	<0.03	<0.03	0.069	0.035	<0.03	<0.03	<0.03	<0.03	<0.03
Magnesium (mg/L)	0.36	0.32	2.7	0.83	1.6	1.3	2.2	1.5	1.1	1.2	0.64	0.5
Manganese (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrate-Nitrogen (mg/L)	0.1	0.1	0.5	<0.1	0.1	<0.1	<0.1	0.25	0.4	0.3	<0.1	<0.1
Potassium (mg/L)	0.3	0.4	0.7	0.7	0.5	0.7	0.5	0.5	1.1	0.9	0.5	0.6
Reactive Phosphorus (mg/L)	0.0058	0.0058	0.0095	0.01	nm	0.027	0.032	0.004	0.016	0.013	<0.01	0.02
Reactive Silica (mg SiO_2/L)	7.9	8.4	17.0	12.0	15.0	13.0	18.0	13.0	13.0	13.0	4.1	3.6
Sodium (mg/L)	1.6	1.9	4.9	2.6	3.3	6.0	4.5	3.5	7.0	5.7	1.4	1.4
Sulphate (mg/L)	1.2	1.2	0.9	4.9	0.7	2.1	0.5	0.6	3.9	3.2	4.5	5.1
Total Hardness (mg $CaCO_3$/L)**	10.0	8.0	31.0	31.0	22.0	35.0	23.0	22.0	44.0	35.0	24.0	23.0
Total Dissolved Solids (mg/L)***	30	28	88	77	66	99	74	65	113	94	51	49
Sum of Anions (meq/L)	0.29	0.26	0.93	0.85	0.65	1.09	0.72	0.67	1.28	1.05	0.61	0.59
Sum of Cations (meq/L)	0.28	0.26	0.86	0.75	0.60	0.98	0.66	0.61	1.22	0.97	0.55	0.54
Ion Balance (% diff)	-2.53	0.23	-4.08	-6.35	-4.03	-5.23	-4.06	-4.83	-2.34	-4.08	-4.88	-4.56
Sodium Absorption Ratio (meq/L)	0.22	0.29	0.38	0.20	0.30	0.44	0.41	0.32	0.46	0.42	0.12	0.13
Oxygen-18 (‰)	-11.27	-11.26	-10.85	-9.68	nm	-10.94	-10.86	-10.68	-11.29	-11.32	-9.56	-9.83

Notes:

Aesthetic Effects - Exceeds 2005 New Zealand Drinking Water Standards (Ministry of Health, 2005) Maximum Acceptable Values

Health Effects - Exceeds 2005 New Zealand Drinking Water Standards (Ministry of Health, 2005) Maximum Acceptable Values

* Parameters measured in the field

** Total Hardness calculated as the sum of Calcium/0.4 and Magnesium/0.24

*** Total Dissolved Solids calculated by summing ion concentrations and reactive silica

nm = not measured

< = parameter not detected at the detection limit shown

Table 4.3: Comparison of results of samples collected in both the 2005 and 2007 period to determine any trends over time.

Year	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005	2007	2005
Well Number	**I37/0009**	**I37/0009**	**I38/0003**	**I38/0003**	**I38/0015**	**I38/0015**	**I38/0052**	**I38/0052**	**I38/0053**	**I38/0053**	**H38/0021**	**H38/0021**	**H38/0025**	**H38/0025**	**H38/0051**	**H38/0051**	**I39/0004**	**I39/0004**	**I39/0007**	**I39/0007**
Well Depth (m)	6	6	48	48	80.8	80.8	2	4	8.9	13	12.2	12.2	4.5	4.03	41	41	68	68	18	18
Depth to Water (m)	nm	nm	-5.33	-6.45	-11.03	-10.65	-0.59	-0.65	-1.4	-0.3	-2.08	-1.78	-1.2	-1.9	-28.5	nm	-5.9	-5.55	-1.5	nm
pH*	9.5	6.9	6.7	6.8	8.2	7.9	6.5	7.0	7.1	6.8	6.6	6.8	6.1	6.0	8.6	7.4	8.4	8.5	7.2	7.1
Water Temperature (°C)*	6.0	13.5	10.2	13.9	10.8	11	7.6	13.1	10.8	13.9	8.2	13.5	8.6	12.8	11.0	13.5	13.2	12.9	10.5	13.9
Conductivity at 25°C (mS/m)*	17.0	7.0	16.7	16.6	16.9	10.6	7.3	7.3	21.3	20.7	3.1	18.7	3.0	3.8	8.4	9.0	13.0	9.7	10.7	11.7
Dissolved Oxygen (mg/L)*	9.3	3.8	10.4	3.4	2.87	1.2	7.7	5.9	4.85	1.9	10.21	6.7	7.49	4.3	7.0	6.5	3.97	0.1	5.65	40.0
Dissolved Oxygen (% saturation)*	75.5	39.0	93.4	32.4	29.8	0.13	64.7	57.0	42.9	19.7	87.0	65.1	64.2	40.5	63.6	64.0	37.9	1.2	50.6	37.7
Alkalinity (mg HCO_3/L)	96	17	69	93	96	49	39	40	111	119	15	16	13	16	45	47	69	50	56	59
Ammonia Nitrogen (mg/L)	0.019	0.009	0.009	0.022	0.18	0.051	0.008	0.01	0.1	0.02	0.017	0.0025	0.009	0.0025	0.014	0.0025	0.011	0.031	0.009	0.006
Calcium (mg/L)	16.0	4.0	13.0	14.0	18.0	6.0	5.3	5.0	18.0	18.0	3.4	3.1	2.8	3.7	11.0	12.0	16.0	9.5	12.0	12.0
Chloride (mg/L)	0.28	0.3	4.2	1.7	1.6	1.8	1.8	1.8	3.0	2.0	0.46	0.3	0.4	0.5	0.37	0.4	1.4	1.5	1.6	1.7
Iron (mg/L)	<0.03	0.015	<0.03	0.17	<0.03	0.015	<0.03	0.015	<0.03	0.015	0.059	0.015	<0.03	0.015	<0.03	0.015	<0.03	0.015	<0.03	0.015
Magnesium (mg/L)	<0.1	0.5	5.6	6.3	3.2	2.7	2.1	2.3	6.7	7.2	0.36	0.4	0.32	0.5	0.83	0.9	1.1	1.1	1.2	1.3
Manganese (mg/L)	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005	<0.01	0.005
Nitrate-Nitrogen (mg/L)	0.4	0.05	1.6	0.7	0.3	0.05	0.1	0.1	0.17	0.1	0.1	0.05	0.1	0.6	<0.1	0.05	0.4	0.05	0.3	0.5
Potassium (mg/L)	13.0	0.4	0.9	1.1	0.6	0.6	0.4	0.5	1.3	1.4	0.3	0.4	0.4	0.4	0.7	0.7	1.1	1.0	0.9	1.1
Reactive Silica (mg SiO_2/L)	8.5	7.0	13.0	14.0	14.0	0.2	12.0	14.0	14.0	15.0	7.9	9.4	8.4	9.8	12.0	13.0	13.0	0.4	13.0	14.0
Sodium (mg/L)	9.4	1.3	8.2	9.3	10.0	9.9	5.2	5.7	12.0	13.0	1.6	1.8	1.9	2.4	2.6	2.7	7.0	6.6	5.7	6.5
Sulphate (mg/L)	4.0	2.0	11.0	4.0	3.7	4.7	1.0	0.8	8.0	7.9	1.2	0.9	1.2	1.2	4.9	4.7	3.9	3.2	3.2	2.9
Total Hardness (mg $CaCO_3$/L)**	40.0	12.0	56.0	61.0	58.0	26.0	22.0	22.0	73.0	75.0	10.0	9.0	8.0	11.0	31.0	34.0	44.0	28.0	35.0	35
Total Dissolved Solids (mg/L)***	148	32	127	138	148	72	67	68	174	176	30	32	28	35	77	81	113	72	94	98
Sum of Anions (meq/L)	1.69	0.336	1.59	1.706	1.72	0.959	0.72	0.731	2.08	2.179	0.29	0.297	0.26	0.344	0.85	0.887	1.28	0.936	1.05	1.112
Sum of Cations (meq/L)	1.54	0.309	1.49	1.653	1.61	0.967	0.67	0.698	2.00	2.088	0.28	0.277	0.26	0.341	0.75	0.810	1.22	0.878	0.97	1.016
Ion Balance (% diff)	-4.74	-4.2	-3.31	-1.6	-3.12	0.42	-3.08	-2.3	-1.90	-2.1	-2.53	-3.5	0.23	-0.44	-6.35	-4.5	-2.34	-3.2	-4.08	-4.5
Sodium Absorption Ratio (meq/L)	0.65	0.90	0.48	1.03	0.57	0.52	0.48	0.53	0.61	1.18	0.22	0.66	0.29	0.68	0.20	1.94	0.46	1.09	0.42	1.36

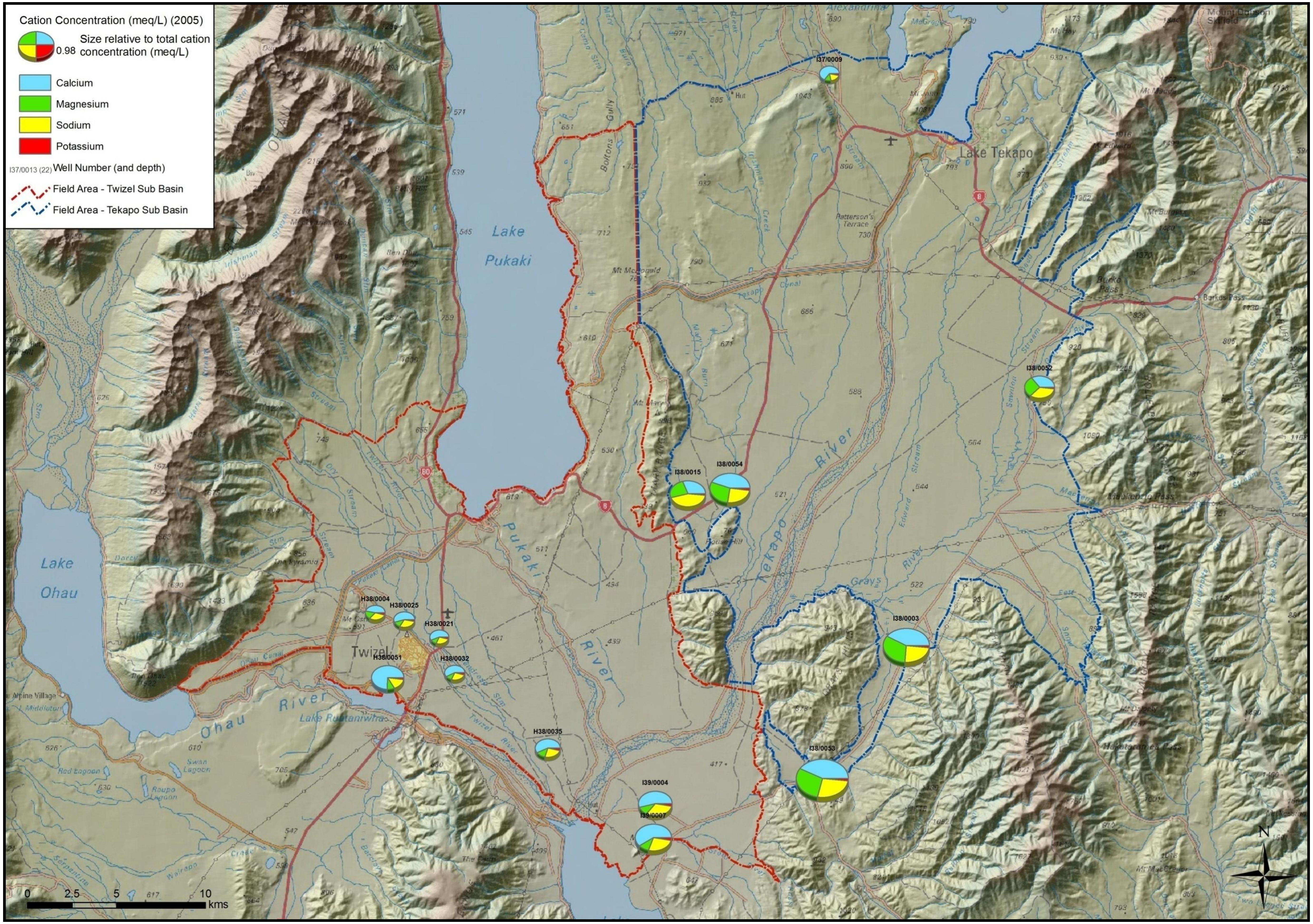


Figure 4.1: Cation concentration throughout the Mackenzie Basin for the February 2005 survey.

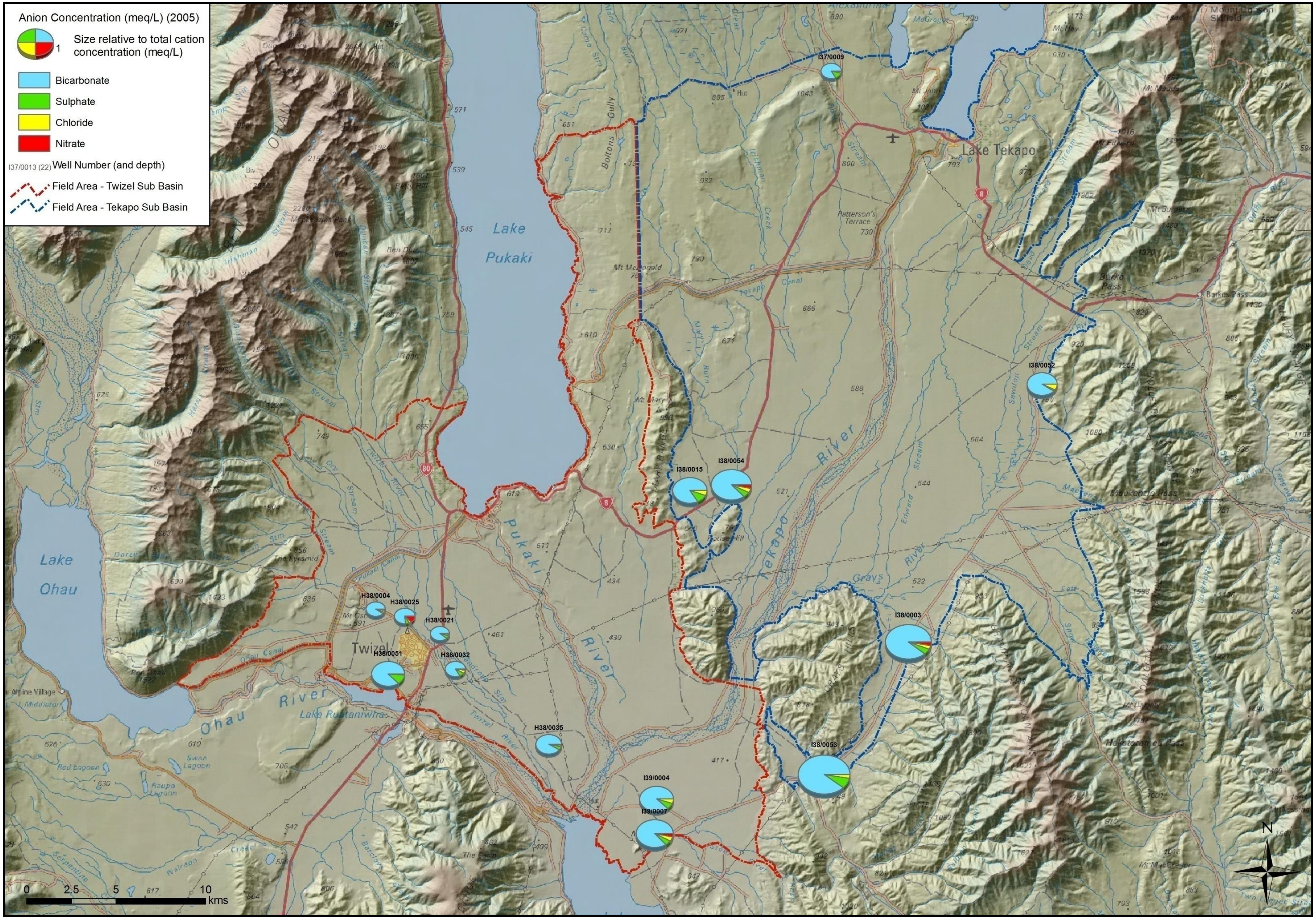


Figure 4.2: Anion concentration throughout the Mackenzie Basin for the February 2005 survey.

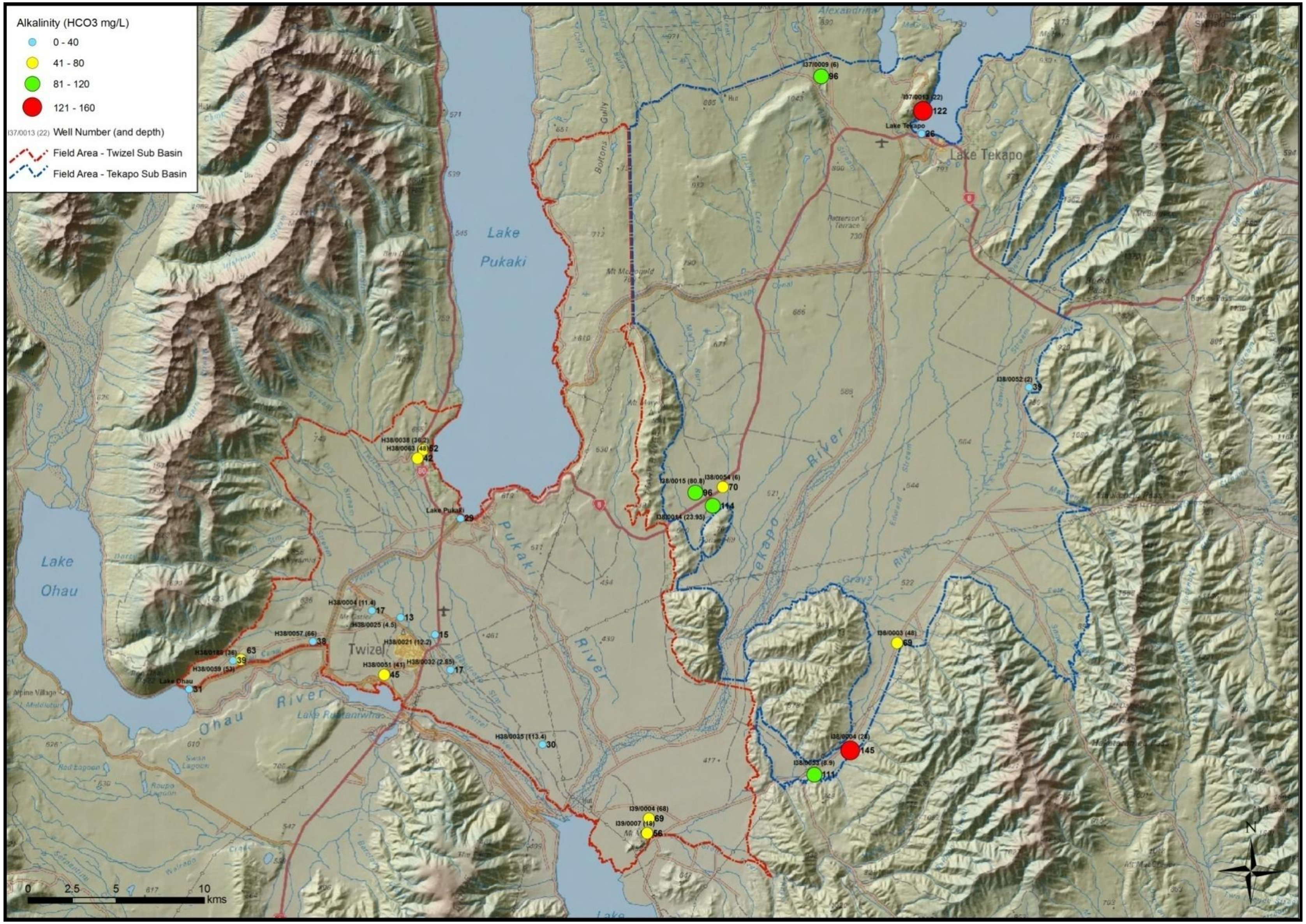


Figure 4.3: Distribution of alkalinity throughout the Mackenzie Basin. Graduated symbols indicate increasing levels of alkalinity.

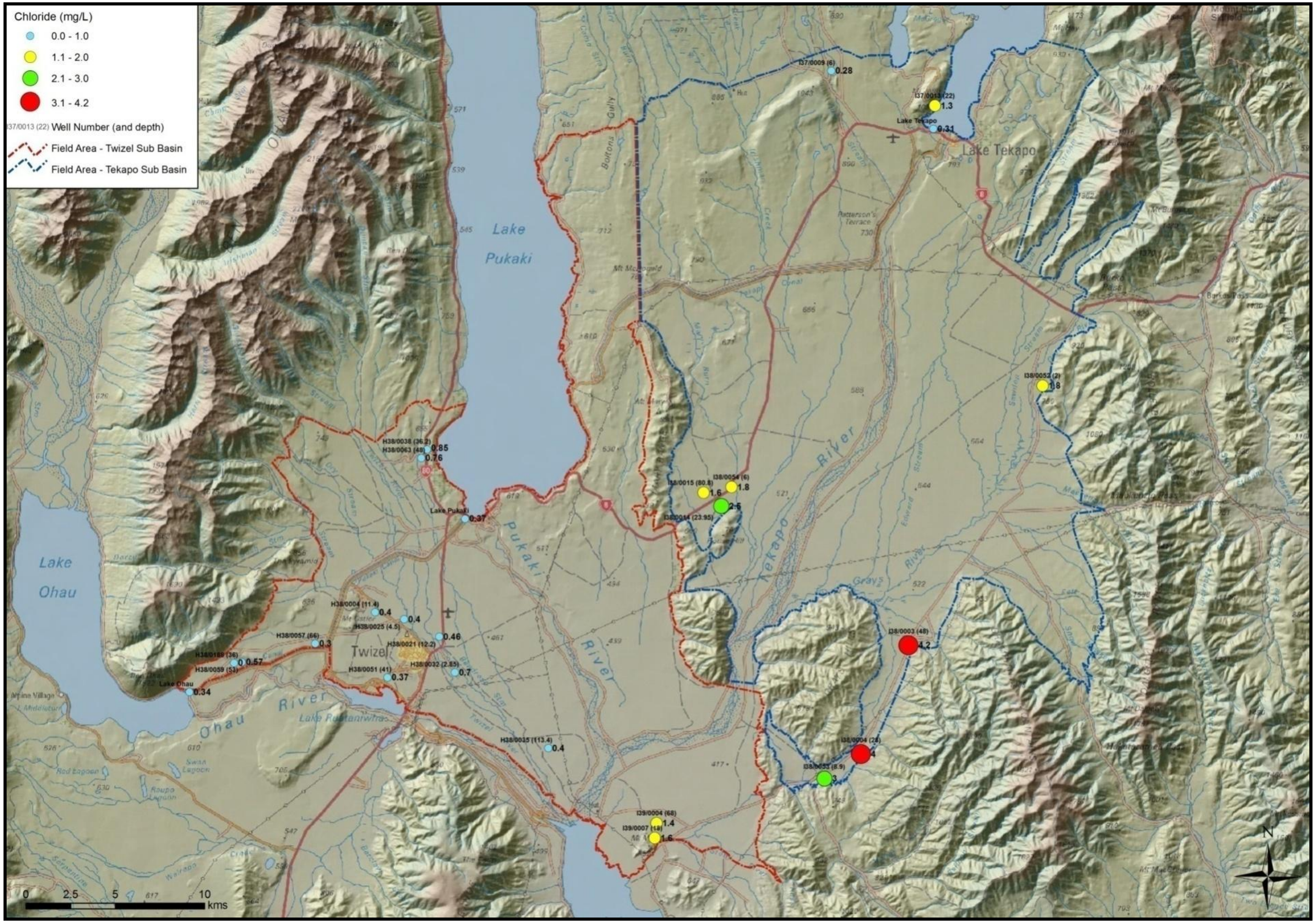


Figure 4.4: Chloride distribution throughout the Mackenzie Basin. Graduated symbols indicate increasing levels of chloride.

Figure 4.5: Nitrate Nitrogen distribution throughout the Mackenzie Basin in October 2007.

Figure 4.6: Nitrate Nitrogen distribution throughout the Mackenzie Basin in February 2005.

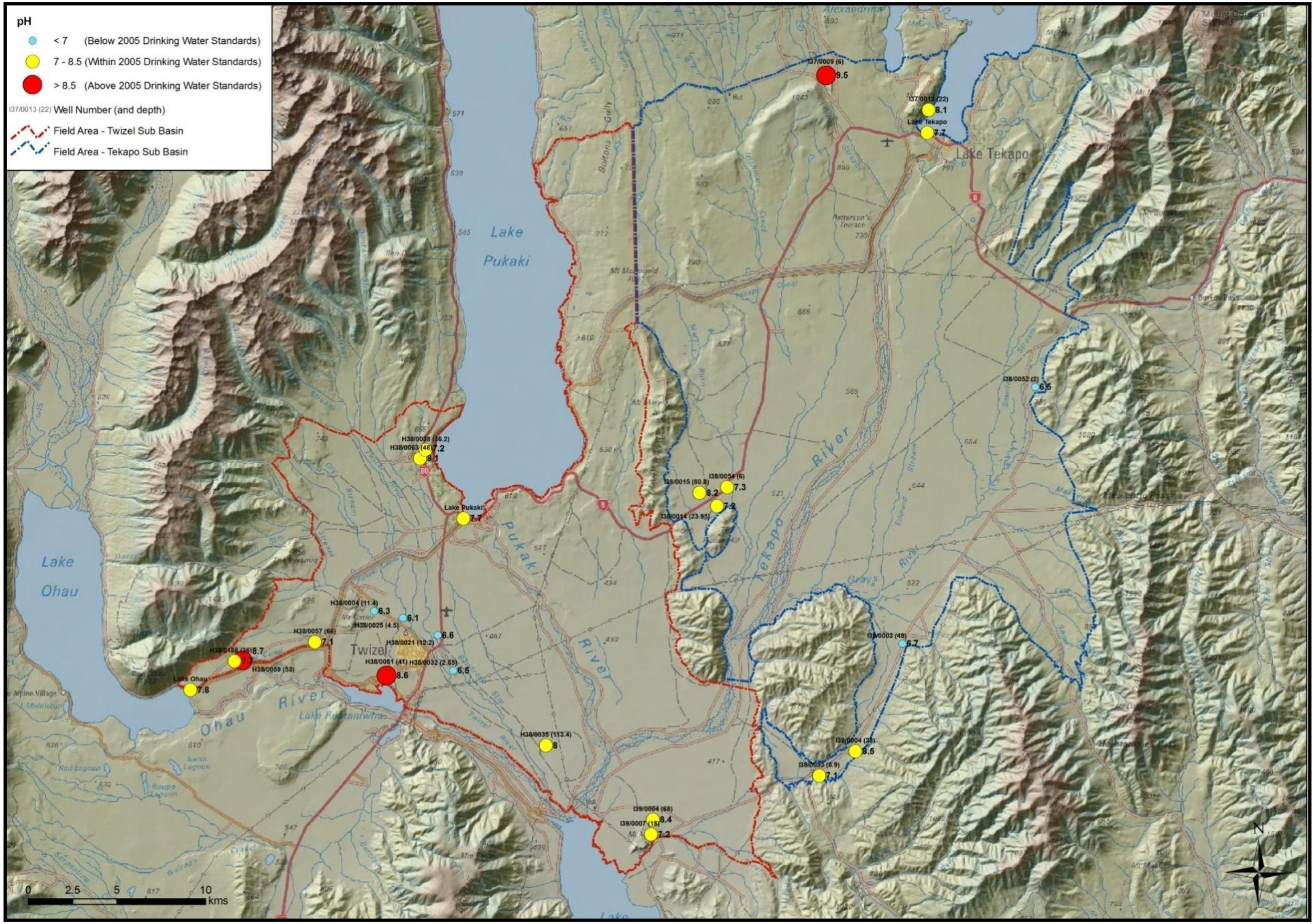


Figure 4.7: Distribution of pH throughout the Mackenzie Basin. Graduated symbols indicate higher pH levels.

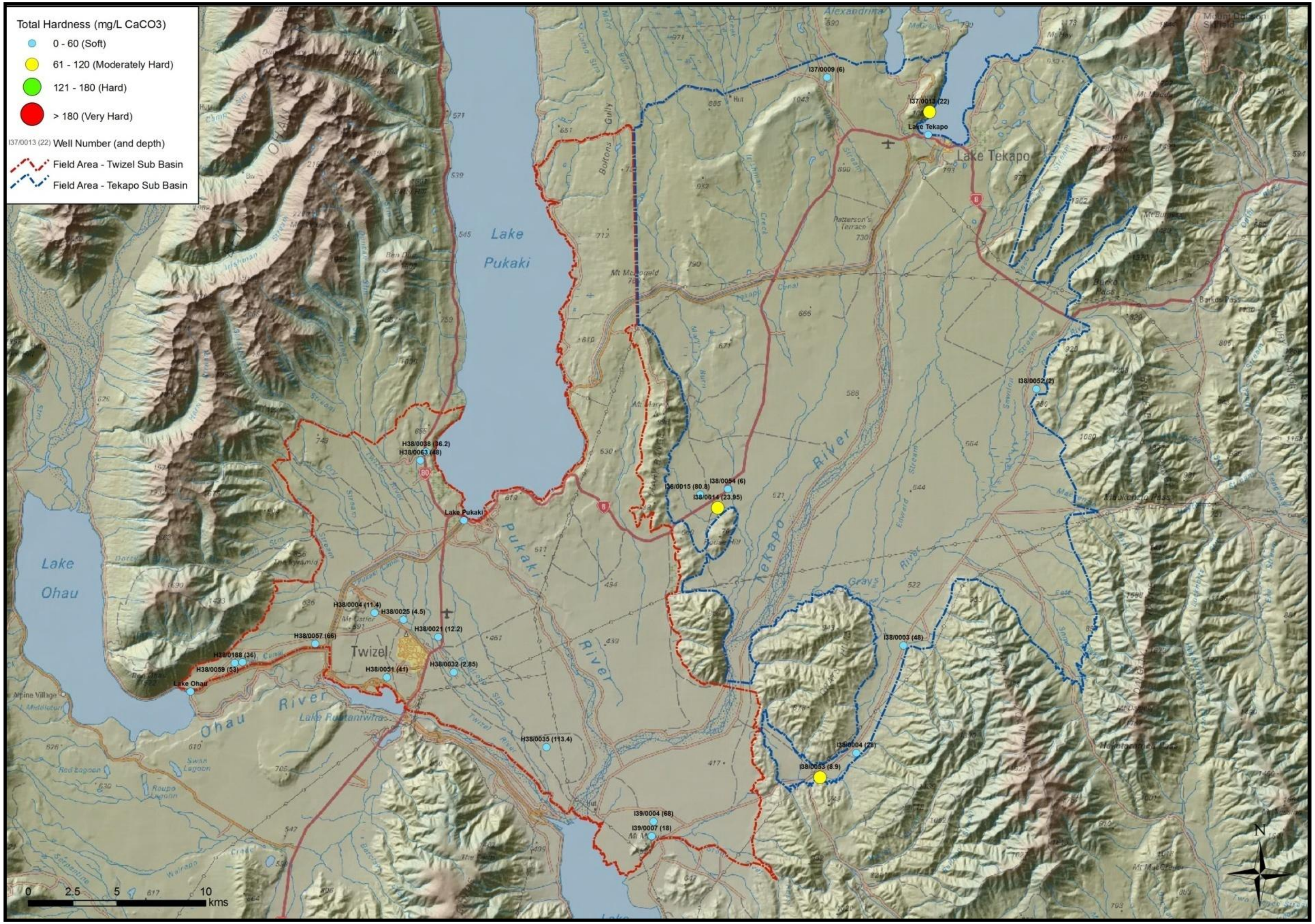


Figure 4.8: Distribution of total hardness throughout the Mackenzie Basin. Graduated symbols indicated increasing levels of total hardness.

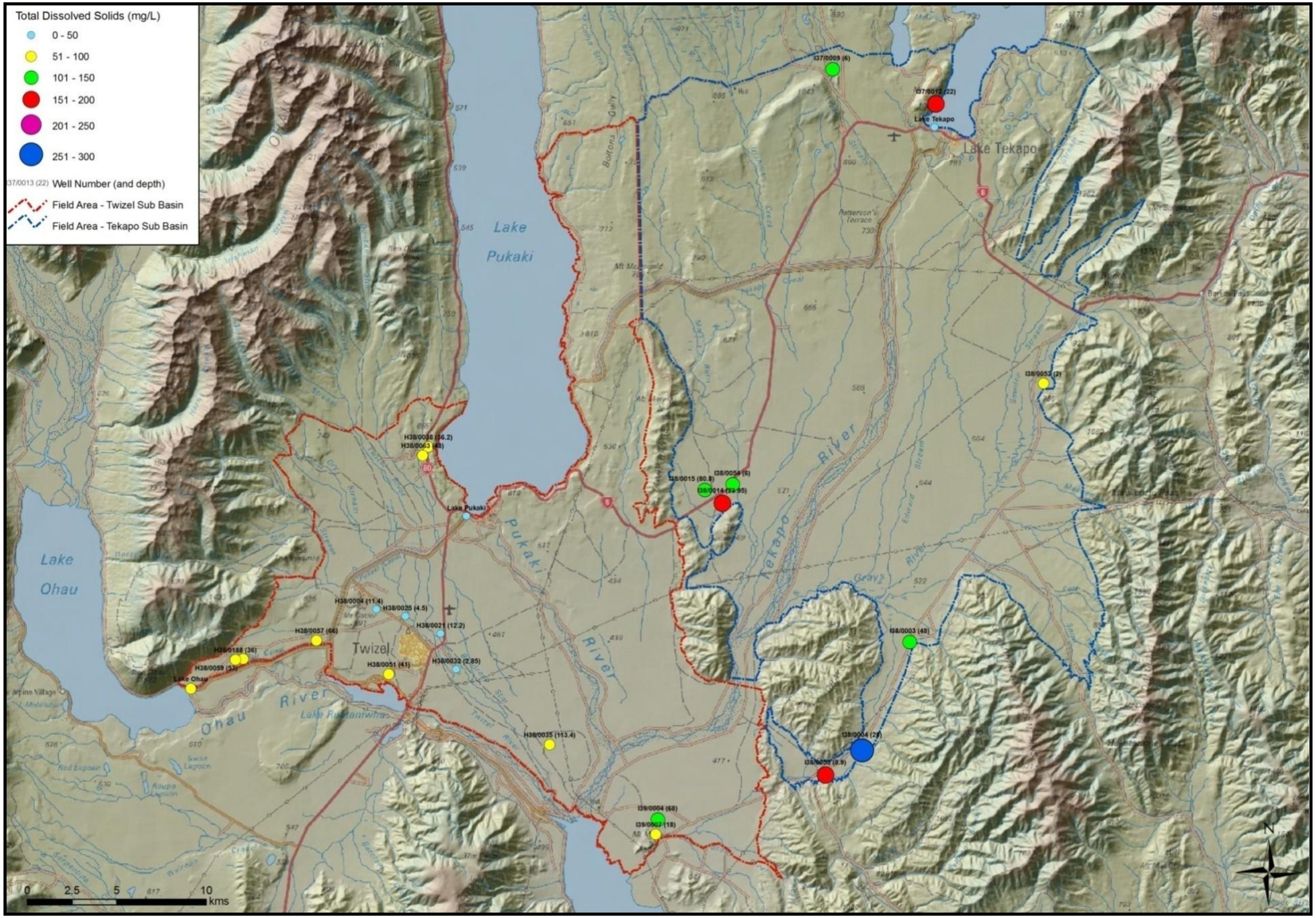


Figure 4.9: Distribution of total dissolved solids throughout the Mackenzie Basin. Graduated symbols indicate increasing levels of TDS.

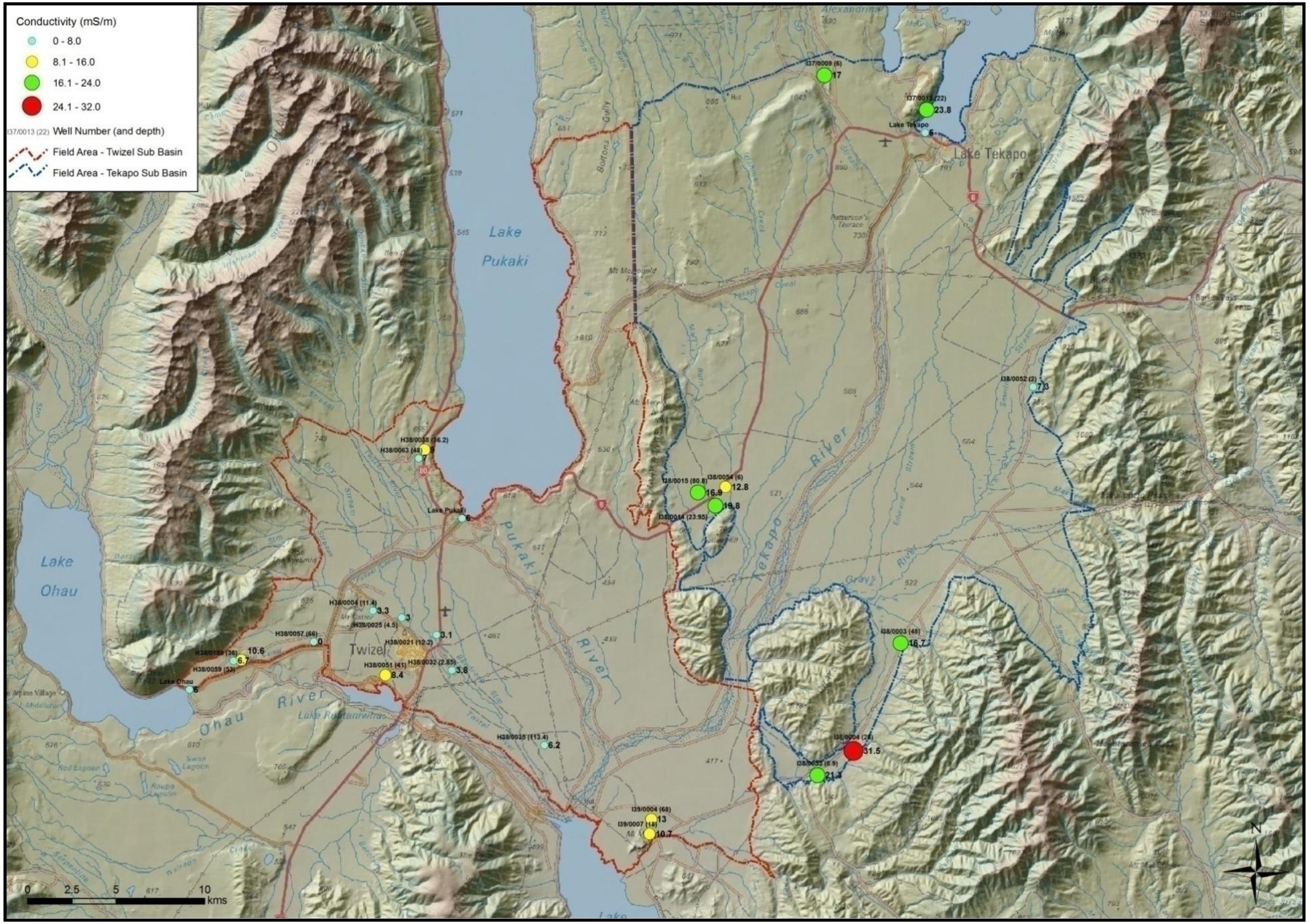


Figure 4.10: Distribution of conductivity throughout the Mackenzie Basin. Graduated symbols indicate higher levels of conductivity.

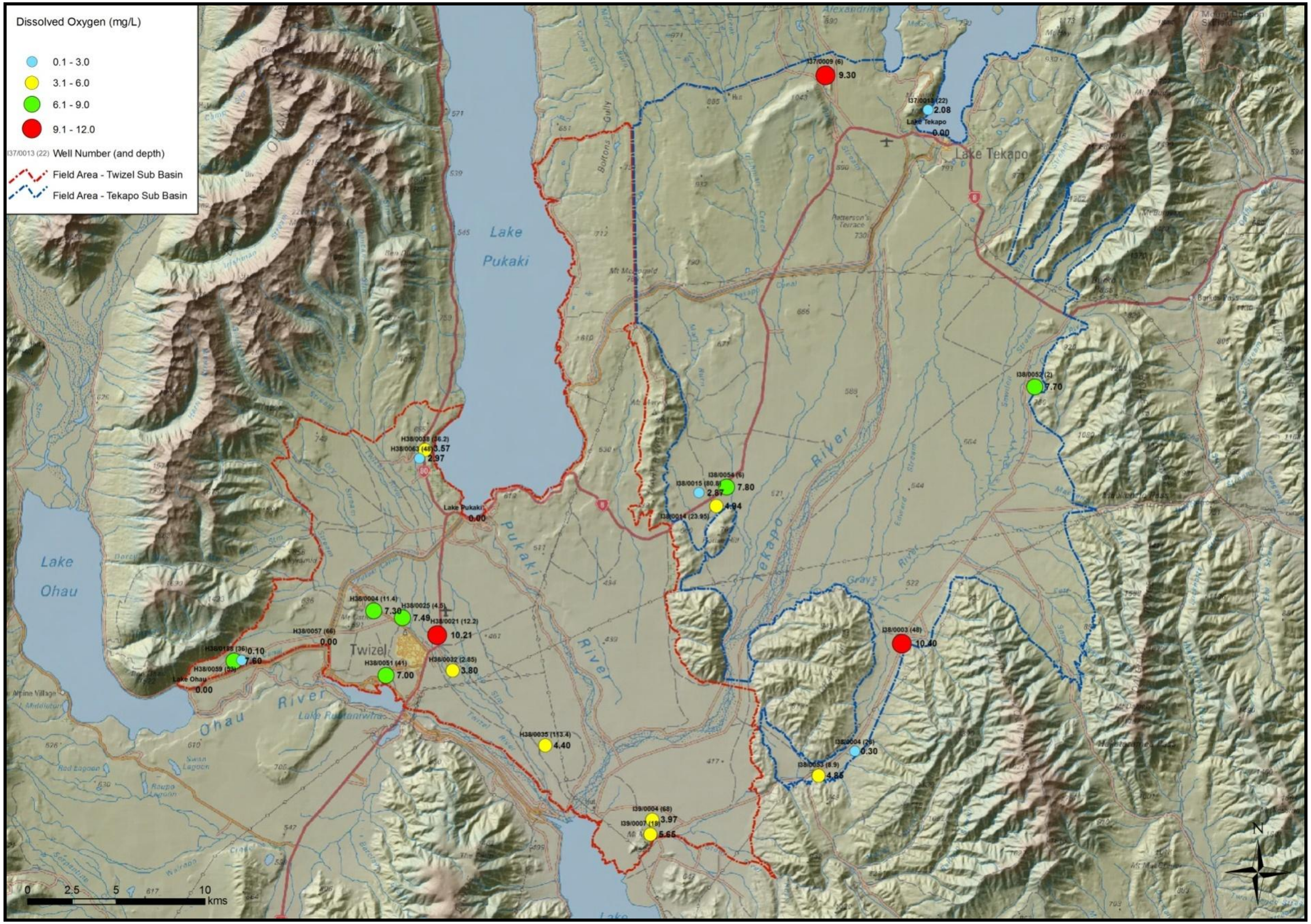


Figure 4.11: Distribution of dissolved oxygen throughout the Basin. Graduated symbols indicate increasing levels of dissolved oxygen.

Appendix 4C

2005 Drinking Water Standards of New Zealand

2005 DRINKING WATER STANDARDS

Table 1: Maximum acceptable values (MAVs) in mg/L for inorganic determinands of health significance

Name	MAV	Remarks
antimony	0.02	
arsenic	**0.01**	**For excess lifetime skin cancer risk of 6 x 10^{-4}. PMAV, because of analytical difficulties**
barium	0.7	
beryllium[1]	0.004	PMAV
boron[2]	1.4	
bromate	0.01	For excess lifetime cancer risk of 7 x 10^{-5}. PMAV
cadmium	0.004	
chlorate	0.8	PMAV. Disinfection must never be compromised. DBP (chlorine dioxide)
chlorine	5	Free available chlorine expressed in mg/L as Cl_2. ATO. Disinfection must never be compromised
chlorite	0.8	Expressed in mg/L as ClO_2. PMAV. Disinfection must never be compromised. DBP (chlorine dioxide)
chromium	0.05	PMAV. Total. Limited information on health effects
copper	2	ATO
cyanide	0.08	Total cyanides
cyanogen chloride	0.08	Expressed in mg/L as CN. Total. DBP (chloramination)
fluoride[3]	**1.5**	
lead	**0.01**	
lithium[1]	1	PMAV
manganese	**0.4**	**ATO**
mercury	0.002	Total
molybdenum	0.07	
monochloramine	3	DBP (chlorination)
nickel	0.02	PMAV
nitrate, short term[4]	**50**	**Expressed in mg/L as $NO_{3.}$ The sum of the ratio of the concentrations of nitrate and nitrite to each of their respective MAVs should not exceed one**
nitrite, long term	0.2	Expressed in mg/L as $NO_{2.}$ PMAV (long term)
nitrite, short term[14]	3	Expressed in mg/L as $NO_{2.}$ The sum of the ratio of the concentrations of nitrate and nitrite to each of their respective MAVs should not exceed one
selenium	0.01	
silver	0.1	PMAV
uranium	0.02	PMAV

Notes: Where WHO Guideline values are based on 60 kg bodyweight, the DWSNZ uses 70 kg bodyweight. See the datasheets for calculations (WHO 2004).

1 MAV retained despite no WHO guideline value.

2 WHO guideline PMAV is 0.5 mg/L.

3 For oral health reasons the Ministry of Health recommends that the fluoride content for drinking-water in New Zealand be in the range of 0.7–1.0 mg/L. This is *not* a MAV.

4 Now short term only. The short-term exposure MAVs for nitrate and nitrite have been established to protect against methaemoglobinaemia in bottle-fed infants.

Table 2: Guideline values (GVs) for aesthetic determinands

Determinand	GV	Units	Comments
aluminium	**0.10**	**mg/L**	**Above this, complaints may arise due to depositions or discoloration.**
ammonia	1.5 0.3	mg/L	Odour threshold in alkaline conditions. For control of chloramine formation in chlorinated water.
calcium			**See hardness.**
chloride	**250**	**mg/L**	**Taste, corrosion.**
chlorine	0.6–1.0	mg/L	Taste and odour threshold (MAV 5 mg/L)
2-chlorophenol	0.0001 0.01	mg/L	Taste threshold. Odour threshold.
colour	10	TCU	Appearance.
copper	1	mg/L	Staining of laundry and sanitary ware (PMAV 2 mg/L)
1,2-dichlorobenzene	0.001 0.002	mg/L	Taste threshold. Odour threshold (MAV 1.0 mg/L)
1,4-dichlorobenzene	0.0003 0.006	mg/L	Odour threshold. Taste threshold (MAV 0.4 mg/L)
2,4-dichlorophenol	0.0003 0.04	mg/L	Taste threshold. Odour threshold.
ethylbenzene	0.002 0.08	mg/L	Odour threshold. Taste threshold (MAV 0.3 mg/L)
hardness (total) **(Ca + Mg) as $CaCO_3$**	**200** **100–300**	**mg/L**	**High hardness causes scale deposition, scum formation. Low hardness (<100) may be more corrosive.** **Taste threshold.**
hydrogen sulphide	0.05	mg/L	Taste and odour threshold.
iron	**0.2**	**mg/L**	**Staining of laundry and sanitary ware.**
magnesium			**See hardness.**
manganese	**0.04** **0.10**	**mg/L**	**Staining of laundry.** **Taste threshold (MAV 0.4 mg/L)**
monochlorobenzene	0.01	mg/L	Taste and odour threshold (MAV 0.3 mg/L)
odour (threshold odour number)	3		Odour should be acceptable.
pH	**7.0–8.5**		**Should be between 7.0 and 8.0. Most waters with a low pH have a high plumbosolvency. Waters with a high pH: have a soapy taste and feel. Preferably pH <8 for effective disinfection with chlorine.**
sodium	**200**	**mg/L**	**Taste threshold.**
styrene	0.004	mg/L	Odour threshold (MAV 0.03 mg/L)
sulphate	**250**	**mg/L**	**Taste threshold.**

Determinand	GV	Units	Comments
taste			Should be acceptable to most consumers.
temperature			Should be acceptable to most consumers, preferably cool.
toluene	0.03 0.04	mg/L	Odour. Taste threshold (MAV 0.8 mg/L)
total dissolved solids	**1000**	**mg/L**	**Taste may become unacceptable from 600–1200 mg/L.**
trichlorobenzenes (total)	see below		(MAV 0.03 mg/L)
1,2,3-trichlorobenzene	0.01	mg/L	Odour threshold.
1,2,4-trichlorobenzene	0.005	mg/L	Odour threshold.
1,3,5-trichlorobenzene	0.05	mg/L	Odour threshold.
2,4,6-trichlorophenol	0.002 0.3	mg/L	Taste threshold. Odour threshold (MAV 0.2 mg/L)
turbidity	2.5	NTU	Appearance. For effective terminal disinfection, median turbidity <1 NTU, single sample <5 NTU.
xylene	0.02	mg/L	Odour threshold (MAV 0.6 mg/L)
zinc	1.5	mg/L	Taste threshold. May affect appearance from 3 mg/L.

Appendix 4D

Graphs and Mass Balance Technique for Source Rock Identification

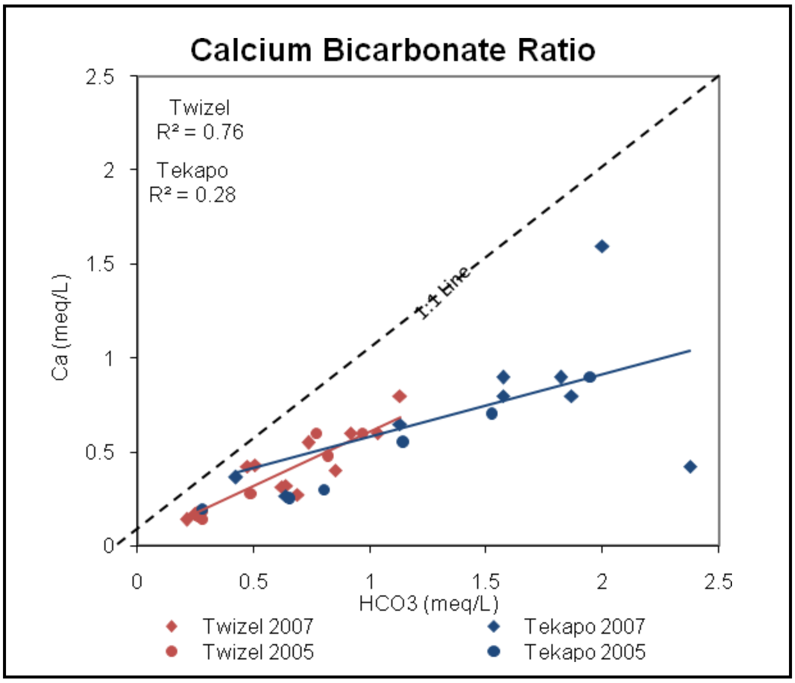


Figure 4.12: Relationship between Ca and HCO_3 for the Twizel and Tekapo sub-basins.

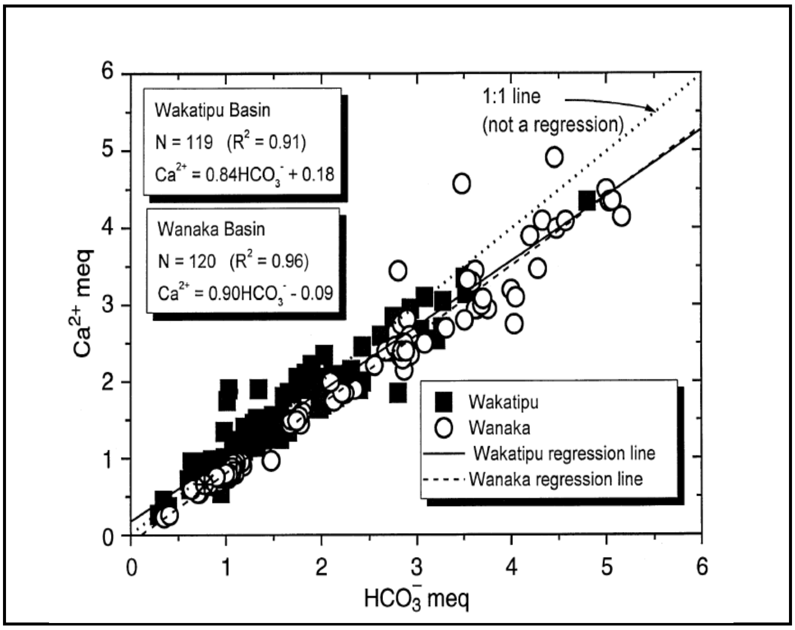


Figure 4.13: Relationship between Ca and HCO_3 for the Wanaka and Wakatipu Basins (Rosen & Jones, 1998).

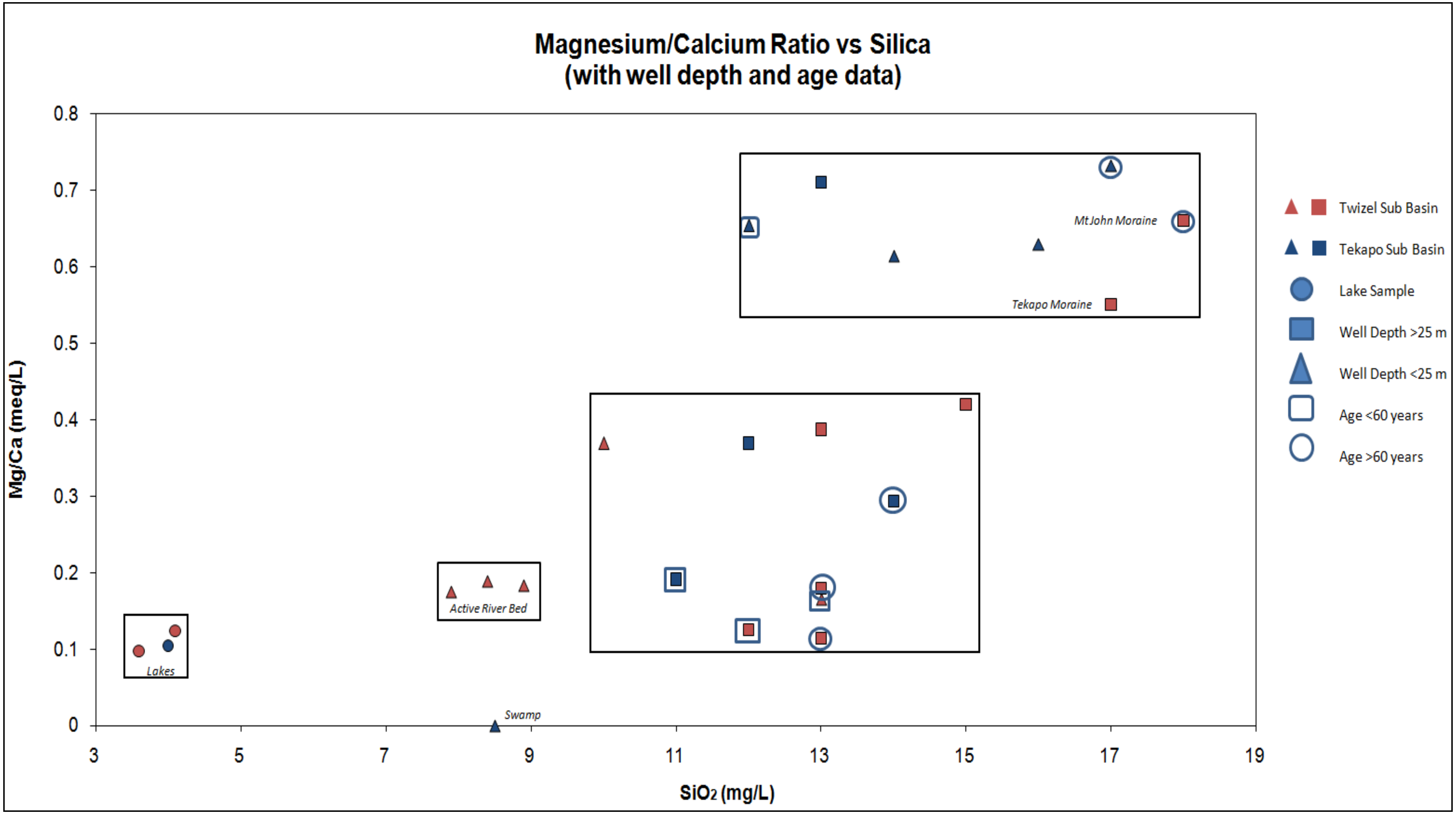


Figure 4.14: Comparison of magnesium:calcium ratio to silica content. The Mg/Ca ratio can provide information on the rock type, while the silica content indicates the amount of weathering. Samples are plotted with respect to well depth, basin location, and age of the sample (where measured). Boxes indicate water samples with similar chemistry analysis data.

SIMPLIFIED MASS BALANCE TECHNIQUE

Well Number	I37/0009		I37/0013		I38/0003		I38/0004		I38/0014		I38/0015		I38/0052	
Parameter	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**
SiO_2 (mmol/L)	0.14	-	0.18	-	0.22	-	0.20	-	0.28	-	0.23	-	0.20	-
$\frac{HCO_3}{SiO_2}$	11.12	carbonate weathering	10.92	carbonate weathering	5.23	ambiguous	11.90	carbonate weathering	6.60	ambiguous	6.75	ambiguous	3.20	silicate weathering
TDS (mg/L)	147.60	silicate weathering	196.41	silicate weathering	126.51	silicate weathering	259.91	silicate weathering	172.32	silicate weathering	148.12	silicate weathering	66.91	silicate weathering
$\frac{SiO_2}{Na + K - Cl}$	-2.48	cation exchange	-0.15	cation exchange	-0.81	cation exchange	0.10	cation exchange	-0.94	cation exchange	-0.52	cation exchange	-7.32	cation exchange
$\frac{Na + K - Cl}{Na + K - Cl + Ca}$	-0.04	plagioclase weathering UNLIKELY	-0.66	plagioclase weathering UNLIKELY	-0.29	plagioclase weathering UNLIKELY	0.73	Plagioclase weathering LIKELY	-0.24	plagioclase weathering UNLIKELY	-0.34	plagioclase weathering UNLIKELY	-0.06	plagioclase weathering UNLIKELY
$\frac{Na}{Na + Cl}$	0.98	Sodium not from halite or albite ion exchange	0.90	Sodium not from halite or albite ion exchange	0.75	Sodium not from halite or albite ion exchange	0.95	Sodium not from halite or albite ion exchange	0.87	Sodium not from halite or albite ion exchange	0.91	Sodium not from halite or albite ion exchange	0.82	Sodium not from halite or albite ion exchange
$\frac{Mg}{Ca + Mg}$	0.00	limestone-dolomite weathering	0.16	limestone-dolomite weathering	0.42	-	0.27	limestone-dolomite weathering	0.42	-	0.23	-	0.40	granitic weathering
$\frac{Ca}{Ca + SO_4}$	0.91	calcium source other than gypsum-carbonates or silicates	0.81	calcium source other than gypsum-carbonates or silicates	0.74	calcium source other than gypsum-carbonates or silicates	0.40	calcium removal -ion exchange or calcite precipitation	0.92	calcium source other than gypsum-carbonates or silicates	0.92	calcium source other than gypsum-carbonates or silicates	0.93	calcium source other than gypsum-carbonates or silicates
$\frac{Ca + Mg}{SO_4}$	9.59	NOT dedolomitization	5.07	NOT dedolomitization	4.84	NOT dedolomitization	0.90	dedolomitization	20.13	NOT dedolomitization	15.08	NOT dedolomitization	21.65	NOT dedolomitization
$\frac{Cl}{\text{Sum of Anions}}$	0.00	Rock weathering	0.02	Rock weathering	0.07	Rock weathering	0.04	Rock weathering	0.03	Rock weathering	0.03	Rock weathering	0.07	Rock weathering
$\frac{HCO_3}{\text{Sum of Anions}}$	0.93	silicate or carbonate weathering	0.82	silicate or carbonate weathering	0.71	?? Seawater or brine...	0.76	?? Seawater or brine...	0.91	silicate or carbonate weathering	0.92	silicate or carbonate weathering	0.89	silicate or carbonate weathering
Debye-Huckel	138.1252	Supersaturated with respect to calcite	12.02925	Undersaturated with respect to calcite	0.131513	Undersaturated with respect to calcite	11.54368	Supersaturated with respect to calcite	0.810992	Undersaturated with respect to calcite	7.603832	Supersaturated with respect to calcite	0.02212	Undersaturated with respect to calcite

Well Number	I38/0053		I38/0054		Lake Tekapo		H38/0004		H38/0021		H38/0025		H38/0032	
Parameter	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**
SiO2 (mmol/L)	0.23	-	0.27	-	0.07	-	0.17	-	0.13	-	0.14	-	0.15	-
HCO3 / SiO2	7.81	ambiguous	4.31	silicate weathering	6.40	ambiguous	1.67	silicate weathering	1.87	silicate weathering	1.52	silicate weathering	1.88	silicate weathering
TDS (mg/L)	174.39	silicate weathering	111.13	silicate weathering	44.04	silicate weathering	33.72	silicate weathering	30.40	silicate weathering	28.48	silicate weathering	34.50	silicate weathering
SiO2 / Na + K - Cl	-0.68	cation exchange	0.35	cation exchange	-0.23	cation exchange	0.37	cation exchange	-1.42	cation exchange	-2.90	cation exchange	0.36	cation exchange
Na + K - Cl / Na + K - Cl + Ca	-0.25	plagioclase weathering UNLIKELY	0.42	Plagioclase weathering LIKELY	-0.68	plagioclase weathering UNLIKELY	0.62	Plagioclase weathering LIKELY	-0.39	plagioclase weathering UNLIKELY	-0.22	plagioclase weathering UNLIKELY	0.55	Plagioclase weathering LIKELY
Na / Na + Cl	0.86	Sodium not from halite or albite ion exchange	0.86	Sodium not from halite or albite ion exchange	0.87	Sodium not from halite or albite ion exchange	0.90	Sodium not from halite or albite ion exchange	0.84	Sodium not from halite or albite ion exchange	0.88	Sodium not from halite or albite ion exchange	0.82	Sodium not from halite or albite ion exchange
Mg / Ca + Mg	0.00	-	0.39	granitic weathering	0.09	-	0.25	granitic weathering	0.15	granitic weathering	0.16	granitic weathering	0.15	granitic weathering
Ca / Ca + SO4	0.84	calcium source other than gypsum-carbonates or silicates	0.88	calcium source other than gypsum-carbonates or silicates	0.81	calcium source other than gypsum-carbonates or silicates	0.93	calcium source other than gypsum-carbonates or silicates	0.87	calcium source other than gypsum-carbonates or silicates	0.85	calcium source other than gypsum-carbonates or silicates	0.87	calcium source other than gypsum-carbonates or silicates
Ca + Mg / SO4	5.39	NOT dedolomitization	12.28	NOT dedolomitization	4.71	NOT dedolomitization	18.65	NOT dedolomitization	7.98	NOT dedolomitization	6.65	NOT dedolomitization	7.85	NOT dedolomitization
Cl / Sum of Anions	0.04	Rock weathering	0.04	Rock weathering	0.02	Rock weathering	0.04	Rock weathering	0.04	Rock weathering	0.04	Rock weathering	0.06	Rock weathering
HCO3 / Sum of Anions	0.87	silicate or carbonate weathering	0.87	silicate or carbonate weathering	0.82	silicate or carbonate weathering	0.91	silicate or carbonate weathering	0.84	silicate or carbonate weathering	0.83	silicate or carbonate weathering	0.84	silicate or carbonate weathering
Debye-Huckel	0.690404	Undersaturated with respect to calcite	0.464903	Undersaturated with respect to calcite	0.312969	Undersaturated with respect to calcite	0.0036038	Undersaturated with respect to calcite	0.0073462	Undersaturated with respect to calcite	0.0016895	Undersaturated with respect to calcite	0.0069491	Undersaturated with respect to calcite

Well Number	H38/0035		H38/0038		H38/0051		H38/0057		H38/0059		H38/0063		H38/0188	
Parameter	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**
SiO2 (mmol/L)	0.23	-	0.28	-	0.20	-	0.25	-	0.22	-	0.30	-	0.22	-
HCO3 / SiO2	2.11	silicate weathering	3.01	silicate weathering	3.69	silicate weathering	2.49	silicate weathering	4.77	silicate weathering	2.30	silicate weathering	2.95	silicate weathering
TDS (mg/L)	54.93	silicate weathering	87.59	silicate weathering	77.42	silicate weathering	65.80	silicate weathering	98.72	silicate weathering	74.07	silicate weathering	64.84	silicate weathering
SiO2 / Na + K - Cl	0.43	cation exchange	-1.63	cation exchange	-0.48	cation exchange	-1.58	cation exchange	-0.67	cation exchange	-4.60	cation exchange	-1.40	cation exchange
Na + K - Cl / Na + K - Cl + Ca	0.50	Plagioclase weathering LIKELY	-0.28	plagioclase weathering UNLIKELY	-0.62	plagioclase weathering UNLIKELY	-0.34	plagioclase weathering UNLIKELY	-0.37	plagioclase weathering UNLIKELY	-0.14	plagioclase weathering UNLIKELY	-0.32	plagioclase weathering UNLIKELY
Na / Na + Cl	0.92	Sodium not from halite or albite ion exchange	0.90	Sodium not from halite or albite ion exchange	0.92	Sodium not from halite or albite ion exchange	0.94	Sodium not from halite or albite ion exchange	0.94	Sodium not from halite or albite ion exchange	0.90	Sodium not from halite or albite ion exchange	1.00	Sodium not from halite or albite ion exchange
Mg / Ca + Mg	0.19	granitic weathering	0.35	granitic weathering	0.11	granitic weathering	0.00	granitic weathering	0.15	granitic weathering	0.40	granitic weathering	0.00	granitic weathering
Ca / Ca + SO4	0.92	calcium source other than gypsum-carbonates or silicates	0.96	calcium source other than gypsum-carbonates or silicates	0.84	calcium source other than gypsum-carbonates or silicates	0.96	calcium source other than gypsum-carbonates or silicates	0.93	calcium source other than gypsum-carbonates or silicates	0.96	calcium source other than gypsum-carbonates or silicates	0.96	calcium source other than gypsum-carbonates or silicates
Ca + Mg / SO4	13.82	NOT dedolomitization	35.40	NOT dedolomitization	6.05	NOT dedolomitization	21.57	NOT dedolomitization	16.14	NOT dedolomitization	40.52	NOT dedolomitization	25.57	NOT dedolomitization
Cl / Sum of Anions	0.02	Rock weathering	0.03	Rock weathering	0.01	Rock weathering	0.01	Rock weathering	0.01	Rock weathering	0.03	Rock weathering	0.00	Rock weathering
HCO3 / Sum of Anions	0.92	silicate or carbonate weathering	0.92	silicate or carbonate weathering	0.87	silicate or carbonate weathering	0.95	silicate or carbonate weathering	0.95	silicate or carbonate weathering	0.95	silicate or carbonate weathering	0.95	silicate or carbonate weathering
Debye-Huckel	0.5707422	Undersaturated with respect to calcite	0.2134225	Undersaturated with respect to calcite	6.0606621	Supersaturated with respect to calcite	0.1004302	Undersaturated with respect to calcite	11.428103	Supersaturated with respect to calcite	0.9803036	Undersaturated with respect to calcite	0.4160591	Undersaturated with respect to calcite

Well Number	I39/0004		I39/0007		Lake Ohau		Lake Pukaki	
Parameter	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**	**Value**	**Conclusion**
SiO_2 (mmol/L)	0.22	-	0.22	-	0.07	-	0.06	-
$\frac{HCO_3}{SiO_2}$	5.23	ambiguous	4.24	silicate weathering	7.45	ambiguous	7.93	ambiguous
TDS (mg/L)	112.91	silicate weathering	93.91	silicate weathering	51.05	silicate weathering	49.13	silicate weathering
$\frac{SiO_2}{Na + K - Cl}$	-0.46	cation exchange	-0.66	cation exchange	-0.19	cation exchange	-0.17	cation exchange
$\frac{Na + K - Cl}{Na + K - Cl + Ca}$	-0.43	plagioclase weathering UNLIKELY	-0.40	plagioclase weathering UNLIKELY	-0.72	plagioclase weathering UNLIKELY	-0.71	plagioclase weathering UNLIKELY
$\frac{Na}{Na + Cl}$	0.89	Sodium not from halite or albite ion exchange	0.85	Sodium not from halite or albite ion exchange	0.86	Sodium not from halite or albite ion exchange	0.85	Sodium not from halite or albite ion exchange
$\frac{Mg}{Ca + Mg}$	0.10	-	0.14	granitic weathering	0.11	-	0.09	-
$\frac{Ca}{Ca + SO_4}$	0.91	calcium source other than gypsum-carbonates or silicates	0.90	calcium source other than gypsum-carbonates or silicates	0.82	calcium source other than gypsum-carbonates or silicates	0.80	calcium source other than gypsum-carbonates or silicates
$\frac{Ca + Mg}{SO_4}$	10.95	NOT dedolomitization	10.47	NOT dedolomitization	5.14	NOT dedolomitization	4.38	NOT dedolomitization
$\frac{Cl}{\text{Sum of Anions}}$	0.03	Rock weathering	0.04	Rock weathering	0.02	Rock weathering	0.02	Rock weathering
$\frac{HCO_3}{\text{Sum of Anions}}$	0.88	silicate or carbonate weathering	0.87	silicate or carbonate weathering	0.83	silicate or carbonate weathering	0.80	silicate or carbonate weathering
Debye-Huckel	7.942597	Supersaturated with respect to calcite	0.321486	Undersaturated with respect to calcite	0.5397	Undersaturated with respect to calcite	0.39723	Undersaturated with respect to calcite

Debye-Hückel Equation (at 25º): $-\frac{0.5085 z^2 i\sqrt{I}}{1+0.3281\, a_i\sqrt{I}}$

Appendix 5A

Oxygen-18 Theory

Oxygen-18 Theory

The ocean can effectively be considered as a source of constant isotopic composition, and natural water sample compositions are compared to prepared water with the isotopic composition of the ocean to determine $\delta^{18}O$ using the standard delta notation where:

$$\delta(‰) = \left(\frac{R_{sample}}{R_{V-SMOW}} - 1\right) \times 1000$$

$R = {}^{18}O/{}^{16}O$

V-SMOW = Standard Mean Ocean Water

Results have an error of ±0.1%

Atmospheric vapour or non-oceanic water that has undergone successive processes of evaporation, condensation, and mixing provides a δ value for the vapour or water. Most of these processes involve, to a degree, isotope separation (fractionation). The nature and magnitude of the fractionation can be used to trace the movement and origin of environmental waters. Fractionation processes generally occur during evaporation and condensation which are variable due to temperature (Dansgaard, 1964). During evaporation heavy isotopes (i.e. ^{18}O and ^{2}H) will be preferentially concentrated in the liquid phase, whereas ^{16}O and ^{1}H will be preferentially concentrated into the vapour phase due to kinetic fractionations. As a result, precipitation has relatively less heavy isotopes when compared to ocean water (Taylor & Stewart, 1978). Generally, δ-values of precipitation will be more negative (depleted in $\delta^{18}O$) at lower temperatures, therefore δ-values of precipitation vary with the season (winter rainfall is more negative than summer), altitude, latitude, and atomospheric circulation patterns (Stewart & Taylor, 1981). It is suggested that the altitude gradient creates an increase of -0.23 ‰ per 100 metres for $\delta^{18}O$ (Dansgaard, 1964). Rain can also be enriched in heavy isotopes by exchange with warmer atmospheric vapour or evaporation as it falls to the ground. Evaporation from falling raindrops is common in arid regions (Stewart & Taylor, 1981).

The effects of altitude and temperature on δ-values have been used to define river or rainfall recharge sources within the Canterbury Plains. Many of the rivers on the plains have a high altitude catchment and the water is therefore more negative in comparison to precipitation directly onto the Canterbury Plains area. This variance suggests that much of the groundwater within the aquifers is being recharged by the major rivers (Stewart & Taylor, 1981). Within the study area this comparison is not as easily differentiated.

In areas of steep slopes, shallow soils overlay low permeability rock (greywacke, schist); there is little hold-up capcaity for large amounts of precipitation and this is usually transmitted through the soil over days to weeks and drained towards the coast via rivers on the Canterbury Plains (Stewart & Taylor, 1981). Snow and ice represent reservoirs for water in the Alps and contribute to spring peak flows in many major rivers. The δ-value for snow (and snow melt water) ranges from -7 at low altitudes to -16 on the highest peaks (Stewart & Taylor, 1981). Once precipitation has infiltrated the soil surface, the isotopic composition of the water can change due to; 1) geographic displacement by surface or subsurface flow and associated mixing of groundwater masses, for example in the Canterbury Plains; 2) the water originating from surface water bodies i.e. lakes; 3) mixing with other waters; 4) chemical interaction of water with aquifer materials; 5) fractionation during water transport (Stewart & Taylor, 1981).

Stewart & Morgenstern (2001) note that in westerly zones $\delta^{18}O$ decreases by 0.21 ‰ per 100 metre increase in altitude due to westerly atmospheric circulation over the Tasman Sea. This circulation brings dry air from Australia and picking up moisture rapidly as it passes over the sea before reaching New Zealand. For easterly zones (for example the Canterbury Plains) the $\delta^{18}O$ are more negative for a given altitude compared to westerly rainfall, as the easterly rainfall is from southeast sources or from westerly air masses that have been depleted in heavy isotopes as they pass over the main divide (Stewart & Morgenstern, 2001).

Appendix 5B

Groundwater Age and Source Analysis Data from GNS

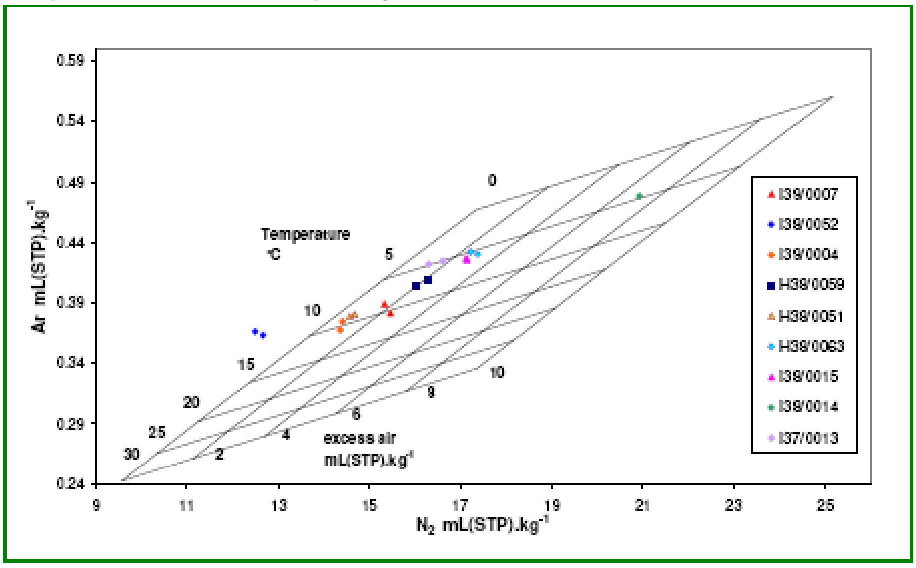


Figure 1: Plot of nitrogen versus argon concentrations. The positions of the samples within the grid indicate their recharge temperatures and excess air concentrations (van der Raaij, 2008).

Table 1: Recharge temperatures and excess air concentrations, calculated atmospheric CFC concentrations during recharge, and piston flow ages of CFC and SF_6 samples (van der Raaij, 2008).

Bore ID	Recharge temp °C	Excess air	Calculated atmospheric partial pressures			Age based on piston flow model (yrs)		
			CFC-11	CFC-12	SF_6	CFC-11	CFC-12	SF_6
I39/0007	10.3 ± 1.3	2.0 ± 0.6	80.7 ± 6.0	0.0 ± 0.0	3.65	34	31	10
I38/0052	6.5 ± 0.7	-3.2 ± 0.6	177.2 ± 6.0	442.3 ± 13.4	6.72	25	19	0
I39/0004	10.7 ± 0.9	0.8 ± 0.3	2.7 ± 0.4	11.7 ± 1.0	0.54	52	53	29
H38/0059	7.2 ± 0.1	2.0 ± 0.2	0.0 ± 0.3	5.6 ± 1.0	0.24	62	57	36
H38/0051	9.1 ± 0.1	0.7 ± 0.1	189.3 ± 1.8	490.9 ± 2.3	6.79	23	16	0
H38/0063	5.1 ± 0.4	2.7 ± 0.3	1.2 ± 0.0	3.8 ± 0.3	0.14	55	59	41
I38/0015	5.8 ± 0.2	2.7 ± 0.1	0.7 ± 0.0	2.9 ± 0.4	0.36	56	59	33
I38/0014	4.7 ± 0.0	7.0 ± 0.0	15.4 ± 0.0	83.2 ± 0.0	0.05	44	40	55
I37/0013	4.0 ± 0.1	1.5 ± 0.3	13.0 ± 0.1	81.4 ± 0.6	1.53	45	40	21

[1] Recharge temperatures are derived from measured argon and nitrogen concentrations
[2] Excess air concentrations are derived from measured argon and nitrogen concentrations and are expressed in mL(STP).kg^{-1}. Negative values indicate sample degassing.
[3] Atmospheric CFC and SF_6 partial pressures are calculated using Henry's Law and the given recharge temperature after correction for excess air.
[4] Atmospheric concentrations are expressed in parts per trillion (ppt). 1 ppt signifies a ratio of 1×10^{-12}

Table 2: Additional sample details and measured sampling parameters (van der Raaij, 2008).

Sample ID	ECan Lab ID	E	N	$\delta^{18}O$ (‰)	Temperature °C	Conductivity	pH	Dissolved oxygen mg.L^{-1}	Dissolved iron mg.L^{-1}	Dissolved methane µmol.L^{-1}
I39/0007	2706883	2291560	5646817	-11.32	10.5	10.74	7.2	5.65	<0.03	--
I38/0052	2706885	2313265	5672144	-11.15	7.6	7.3	6.5	7.7	<0.03	--
I39/0004	2706886	2291660	5647650	-11.29	13.2	13.02	8.36	3.97	<0.03	--
H38/0059	2706888	2268440	5656640	-10.94	11.2	10.6	8.7	**0.1**	**0.07**	**1.6 ± 0.2**
H38/0051	2706890	2276618	5655816	-9.68	11.0	8.43	8.56	7.0	<0.03	--
H38/0063	2706892	2278510	5668102	-10.86	10.4	7.04	8.07	**2.97**	**0.03**	--
I38/0015	2706894	2294292	5666153	-12.13	10.8	16.89	8.24	**2.87**	<0.03	**15.0 ± 0.0**
I38/0014	2706895	2295280	5665404	-11.08	10.3	19.82	7.2	4.94	<0.03	--
I37/0013	2706896	2307233	5687820	-12.48	9.8	23.83	8.05	2.08	<0.03	--
I38/0003	2706884	2305769	5657621	-12.37	--	--	--	--	--	--
I38/0004	2706887	2303110	5651520	-11.86	--	--	--	--	--	--
H38/0025	2706889	2277547	5659071	-11.26	--	--	--	--	--	--
H38/0021	2706891	2279518	5658092	-11.27	--	--	--	--	--	--
H38/0038	2706893	2278823	5668570	-10.85	--	--	--	--	--	--
I37/0009	2706897	2301450	5689780	-10.54	--	--	--	--	--	--
Lake Pukaki canal	2706900	2280888	5664628	-9.83	--	--	--	--	--	--
Lake Ohau canal	2706901	2265614	5655013	-9.56	--	--	--	--	--	--
Lake Takapo inlet	2706902	2307070	5686575	-9.89	--	--	--	--	--	--

[†] Values in bold text are indicative of anoxic conditions within the aquifer under which CFC degradation may occur.

Appendix 5C

Groundwater Age Dating Methods and Problems

5.2 Chlorofluorocarbons

Chlorofluorocarbons (CFCs) (CFC-11 and CFC12) are man-made contaminants from refrigeration, air conditioning units, and aerosol cans. Concentrations within the atmosphere have gradually increased from a level of zero in 1940 to present day values of several parts per trillion (Stewart & Morgenstern, 2001) (Figure 5.1). Since the 1990's, levels of CFCs have slowly been decreasing as their household and industrial use decreases due to their adverse affects on the ozone layer, which therefore makes CFCs as a dating tracer less useful for younger water and may provide ambiguous results (Vincent, 2007). Factors that can modify CFC ages include:

- microbial degradation in anaerobic environments, which reduces CFCs
- contamination from local anthropogenic sources, creating excess CFCs
- CFCs travel faster than water through the unsaturated zone
- CFC solubility is affected by temperature causing errors in estimated recharge temperatures resulting in inaccurate ages
- difficult sampling techniques are required as air must be rigorously excluded from the sample (Stewart & Morgenstern, 2001).

CFC concentrations are corrected for excess air and recharge temperatures using the ratio of dissolved argon and nitrogen, which are measured at the same time as CFC concentrations (van der Raaij, 2008).

5.3 Sulphur Hexafluoride

Sulphur hexafluoride (SF_6) is a man-made gas used in the electricity industry in switch gear as insulation. Concentrations have gradually increased since 1970 and are continuing to rise making SF_6 useful for dating young waters (Stewart & Morgenstern, 2001; Vincent, 2007) (Figure 5.1). Contamination or degradation impacts less on SF_6 concentrations within groundwater compared to CFCs (Vincent, 2007).

5.4 Tritium

The unstable radioisotope tritium (^3H), with a half life of 12.3 years, is used for dating groundwater less than 100 years old. Tritium is naturally produced by cosmic rays, but large amounts were released into the atmosphere during the nuclear bomb testing era in the 1960's. The peak and decay of tritium concentrations within New Zealand are illustrated in Figure 5.1.

Tritium is a useful age dating tracer as its atmospheric concentrations have varied over time; rainfall infiltration reflects tritium concentrations at the time of recharge; it moves with groundwater because it forms part the water molecule; and tritium is not affected by any subsurface processes apart from radioactive asymptotic decay (Vincent, 2007). Tritium concentrations decrease over time within groundwater due to radioactive decay, making the tritium concentration a function of time (Stewart & Morgenstern, 2001). However, the ages provided by tritium can be ambiguous as tritium levels in the atmosphere peaked during the 1960's and have remained nearly constant since approximately 1985 (Figure 5.1), creating three different possible ages for water samples (Stewart *et al.*, 2002). This ambiguity can be overcome by comparing tritium with CFCs and SF_6 ages or by measuring tritium concentrations over a period of a few years (van der Raaij, 2008).

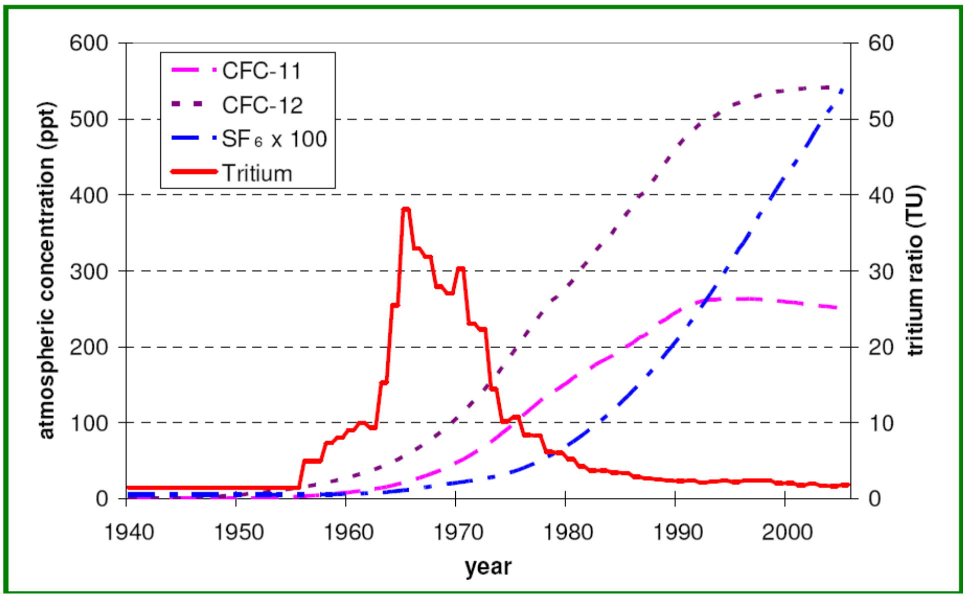
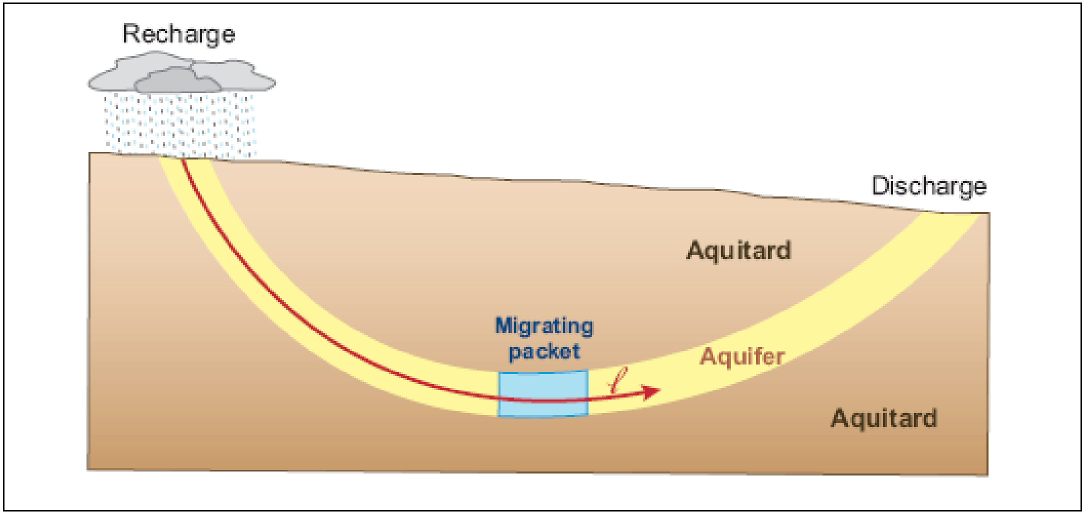


Figure 5.1: Tritium concentrations in rainfall at Kaitoke, New Zealand, and CFC and SF_6 levels in the Southern Hemisphere atmosphere (van der Raaij, 2008).

5.5 Age Dating Analysis Methods

Benthke & Johnson (2008) define the age (or residence time) of groundwater as "the interval of time that has elapsed since groundwater at a location in a flow regime entered the subsurface". Initially, groundwater was thought to enter the subsurface at a recharge point and move through a closed system as a migrating packet (Figure 5.2), and this concept is known as the piston flow model.



1.2: Example of the piston flow model used in groundwater age dating techniques. The migrating package of water moves from the recharge to discharge point without exchanging water molecules along the way (Benthke & Johnson, 2008).

Hydrodynamic, longitudinal, and transverse dispersion of groundwater within aquifers occurs where groundwater moves either through variable flow paths within an aquifer or between different aquifers due to well pumping (Stewart, 2006; Benthke & Johnson, 2008) (Figure 5.3). Mixing and dispersion of groundwater will result in well water with a range of ages from young to old, and is therefore characterised by a mean age (Stewart, 2006; Vincent, 2007).

Benthke & Johnson (2008) suggest that closed packet systems are not realistic, and that a groundwater sample is a collection of water molecules that have entered the system at possibly different periods of time, and that each water molecule has its own age (Figure 5.4). Due to flow velocity groundwater is generally older than expected (Benthke & Johnson, 2002). Groundwater age is controlled by transport in three dimensions which is defined as age mass. In groundwater systems where aquitards dominate over aquifers (90% of the section is aquitard material) it has been calculated that, in steady state situations, groundwater migrates ten times faster than expected from conventional analysis (Benthke & Johnson, 2002). However, steady state conditions do not always apply in natural environments and it has been noted that groundwater in thick clay beds deposited by recent glacial events may be younger than in a steady state situation (Benthke & Johnson, 2002). By calculating transport rates it can be seen that age mass passes from aquitards to aquifers at a rate controlled by the ratio of water mass in aquitards to that of aquifers, and is independent of the rate of mass transfer. Through modelling it has been shown that impermeable aquitards have the same effect as permeable aquifers on groundwater age. Transport modelling is required to determine the relationship between groundwater age and the distribution of an isotope that decays radioactively (Benthke &

Johnson, 2002). It is therefore possible that in both fractured rock systems and areas where aquitard material is prominent, that older water molecules can be transported over time from these sites into flowing aquifers creating a complex mixing of groundwater ages.

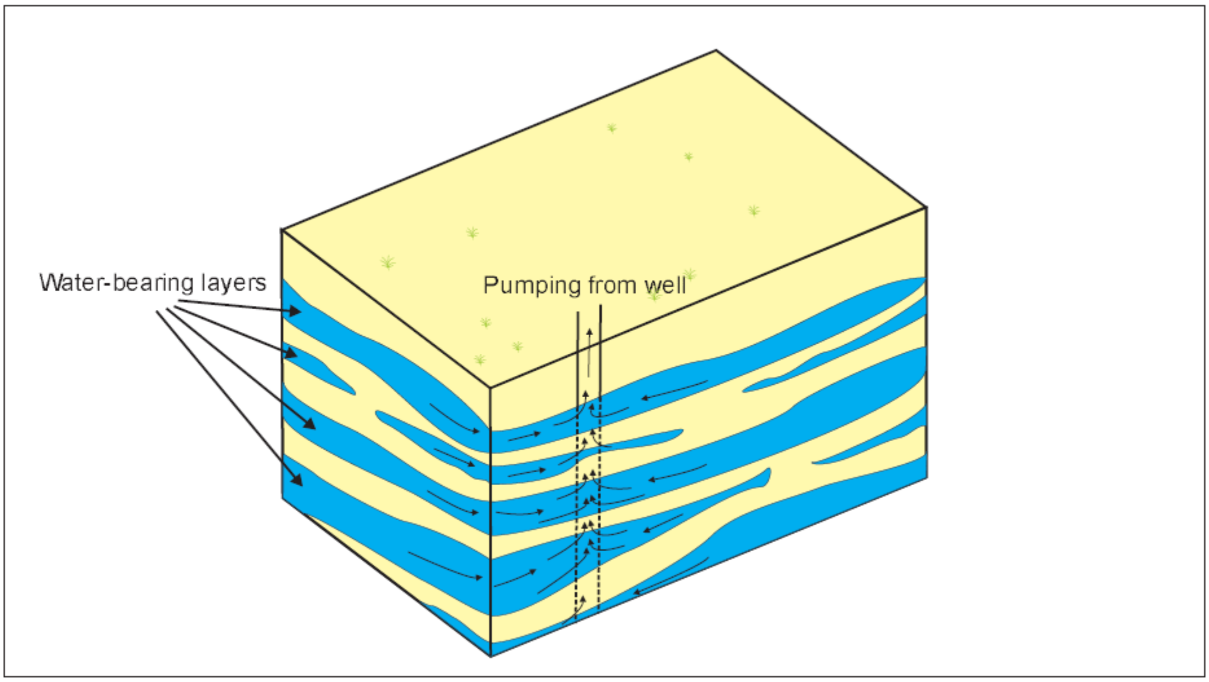


Figure 5.3: The mixing of waters of different ages can occur through flow through variable flow paths or pumping in wells that are screened through multiple water bearing layers. When this type of well is sampled for age analysis the result can produce a wide range of ages for the groundwater (Vincent, 2007).

The effects of three dimensional, geological heterogeneity on groundwater mixing and age dating tracer concentrations have been modelled by Weissman *et al.* (2002) using numerical groundwater flow and transport simulations in conjunction with geostatistical realisations. The results indicated that groundwater supplying a well in a heterogeneous stream dominated alluvial fan system consisted of a wide distribution of groundwater ages, often spanning more than 50 years. It is noted that the results of this study emphasise the ambiguity of 'mean' groundwater ages using environmental tracers in heterogeneous geological systems.

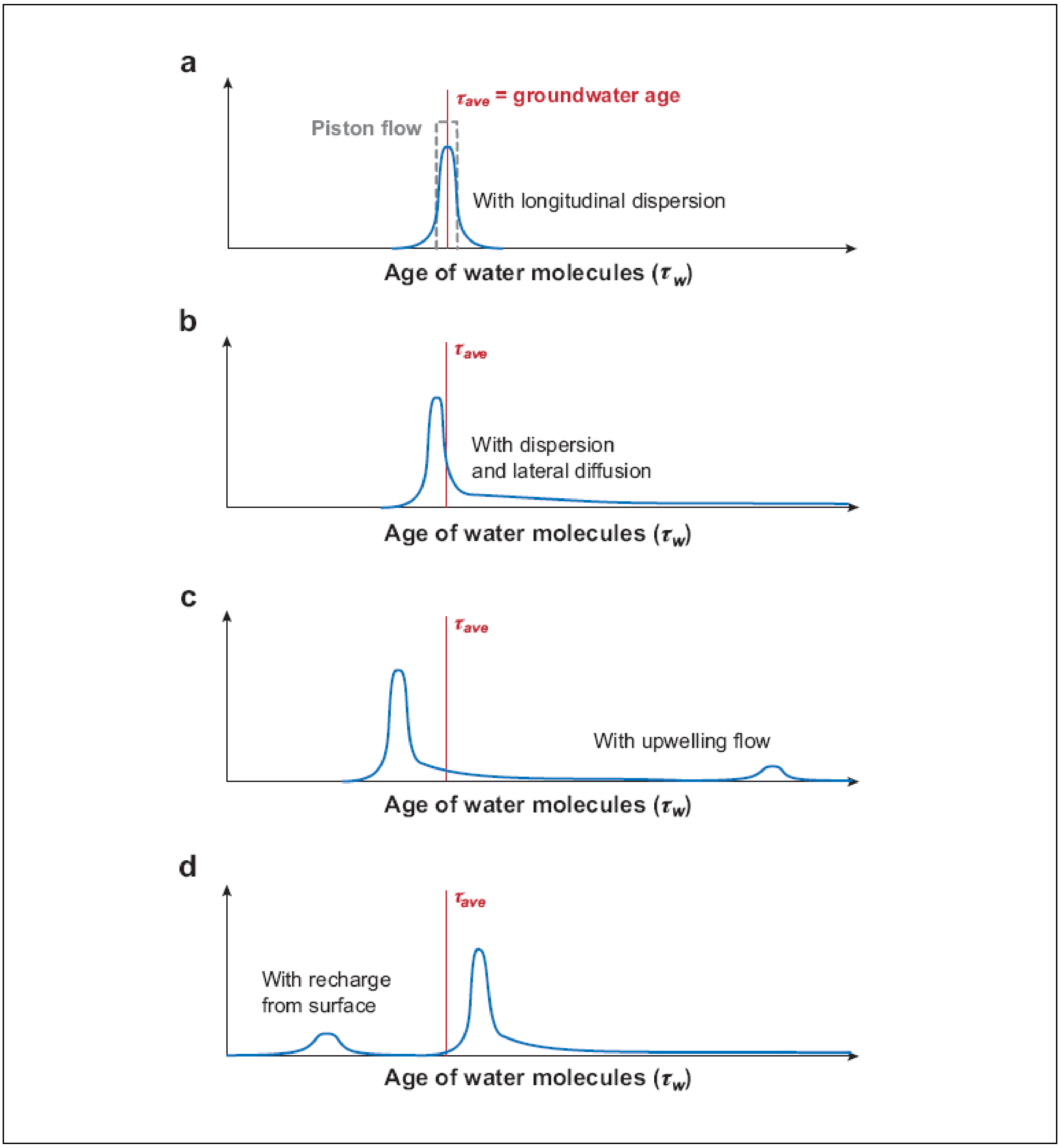


Figure 5.4: An illustration of the different ways in which a groundwater sample with a given age may be composed. Groundwater age, τ_{ave}, is the average over the ages, τ_w, of water molecules in the sample. (a) water molecules recharged at approximately the same time which move along the aquifer as a piston, or a piston subject to longitudinal dispersion; (b) water which is affected by longitudinal dispersion and exchange by diffusion of water molecules with neighbouring aquitards; (c) the water age is influenced by the upwelling of older groundwater; (d) young water is recharging the aquifer from the surface (Benthke & Johnson, 2008).

Vincent (2007) suggests that groundwater flowing through unconfined or semi-confined aquifers will have an exponential age distribution, whereas groundwater within a confined aquifer moves as a 'front' with little mixing and dispersion taking place, and suggests that piston flow models can be used for this scenario. Stewart & Morgenstern (2001) suggest that the mixing of groundwater is likely to be in the range of 60 ± 20% and therefore uses an exponential piston flow model with 60% mixing to interpret ages. The higher the percentage used for the flow model, and therefore the higher degree of mixing, will result in a wider range of ages (Vincent, 2007). Sampling more wells, and in particular sampling a well more than once, can give a better indication of which exponential flow model should be used. The amount of exponential mixing within any well is dependent on the hydrogeologic attributes of the aquifer in conjunction with the characteristics of the sampling point (van der Raaij, 2008).

For methods that use asymptotic decay, such as tritium, the sample ages calculated for water that are a mixture of sources can be quite biased strongly towards youth (Benthke & Johnson, 2008). It is suggested that the distribution of groundwater age across a flow regime can be calculated by tracking the generation and transport of age mass, the product of groundwater age and mass (Benthke & Johnson, 2008). Reactive transport modelling can incorporate chemical and physical observations of the subsurface to help define flow rates and regimes. The models can be constrained using data collected from stratigraphic units rather than a single aquifer to characterise flow and transport in multiple dimensions throughout an entire groundwater flow system (Benthke & Johnson, 2008).

Zuber *et al.* (2005) have used transport modelling and hydrochemistry, in conjunction with age tracers, as part of a study of sandy aquifers in southern Poland. It was determined that hydrochemical zones were consistent with age tracer data, and that young waters were dominated by Ca-HCO_3 and SO_4-Ca-HCO_3 and were aerobic. Very old water within the study area was found to have anaerobic conditions with elevated levels of total dissolved solids, phosphate, and sodium relative to calcium. Higher total dissolved solid values and elevated sodium content were thought to be from small admixtures of ascending or diffusing older water or water flushing through marine sediments. (Zuber, et al., 2005).

Daughney *et al.* (2007) have created an algorithm to 'predict' the age of groundwater based on the hydrochemistry, conductivity, and well depth. The statistical method is being calibrated using data from the National Groundwater Monitoring Programme (NGMP). Once calibrated, it is suggested that groundwater age can be predicted based on hydrochemistry alone.

Appendix 5D

Groundwater Age Versus Other Parameters - Graphs

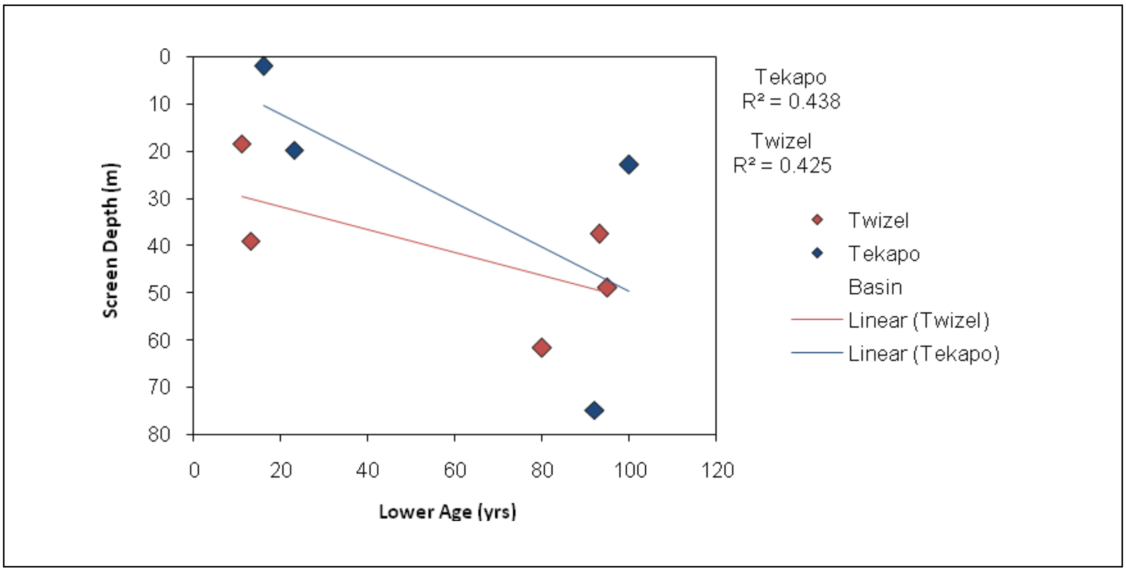


Figure 1: Lower groundwater age in comparison to screen depth within the well.

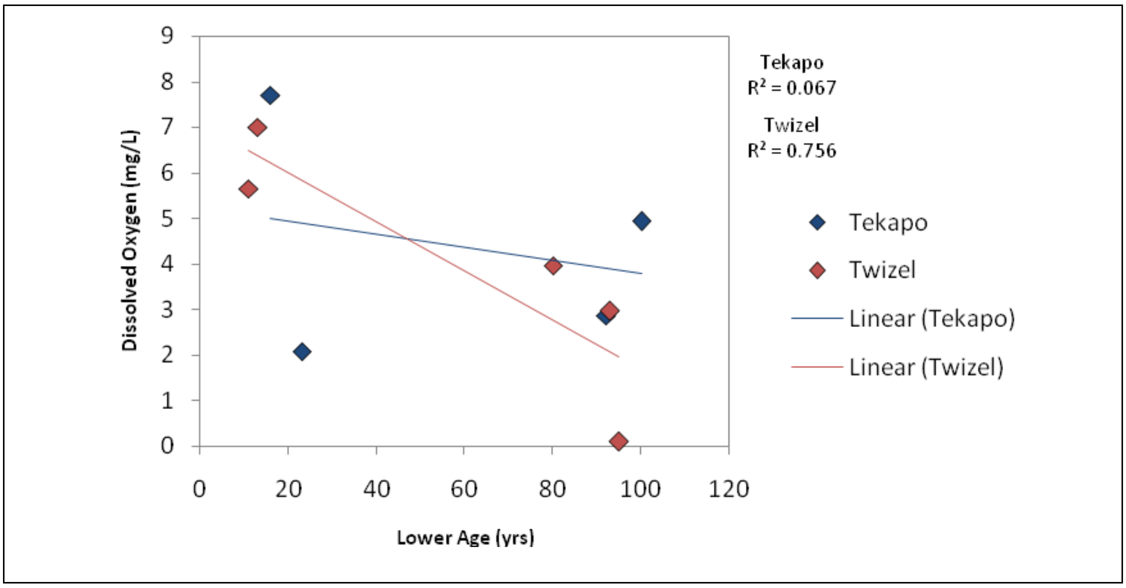


Figure 2: Lower groundwater age in comparison to dissolved oxygen concentrations.

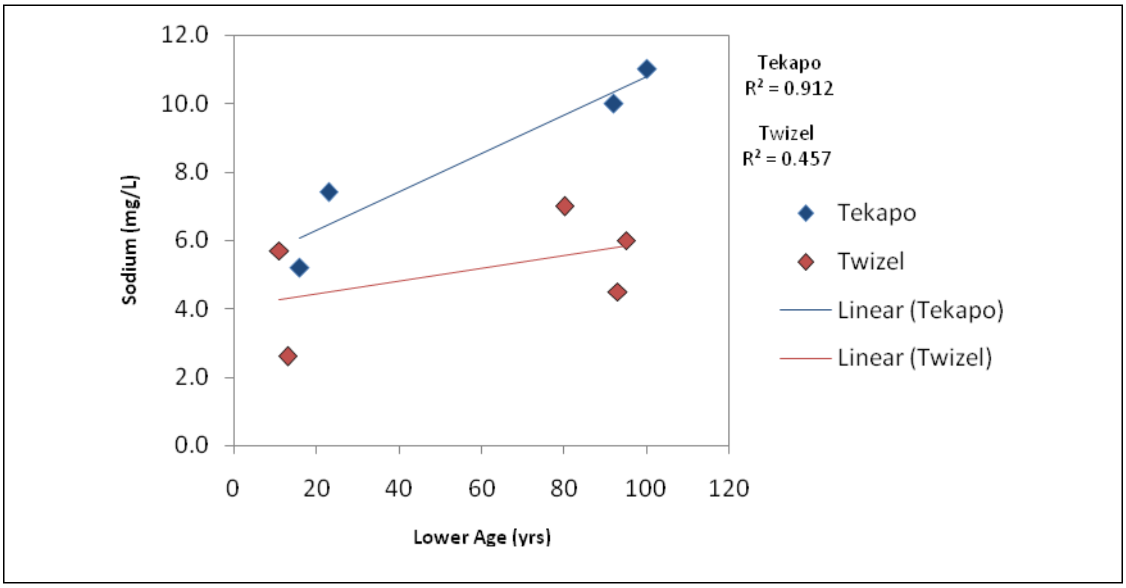


Figure 3: Lower groundwater age in comparison to sodium concentrations.

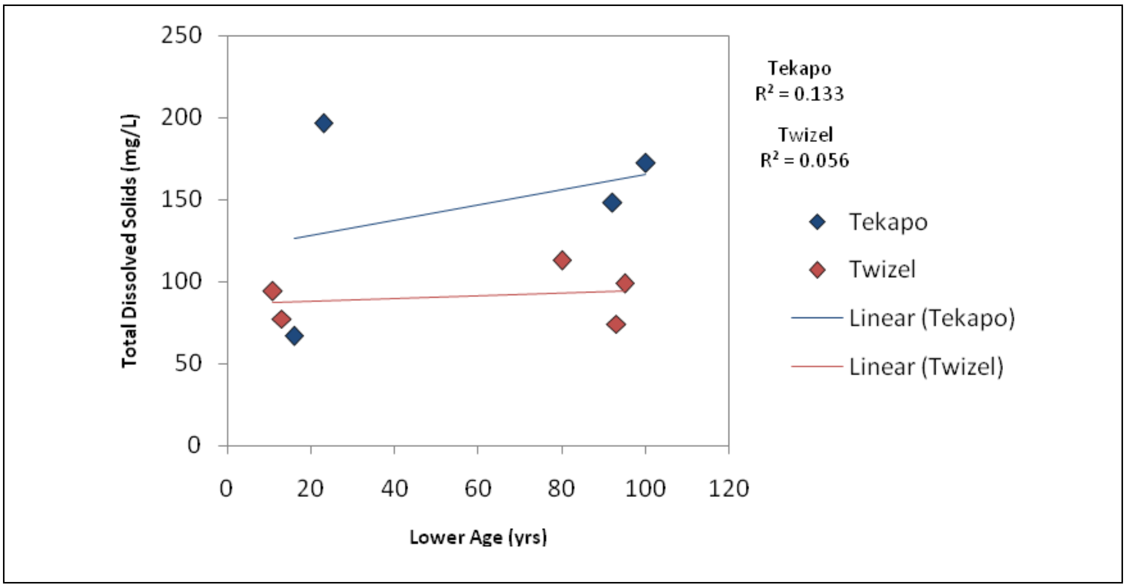


Figure 4: Lower groundwater age in comparison to total dissolved solids concentrations.

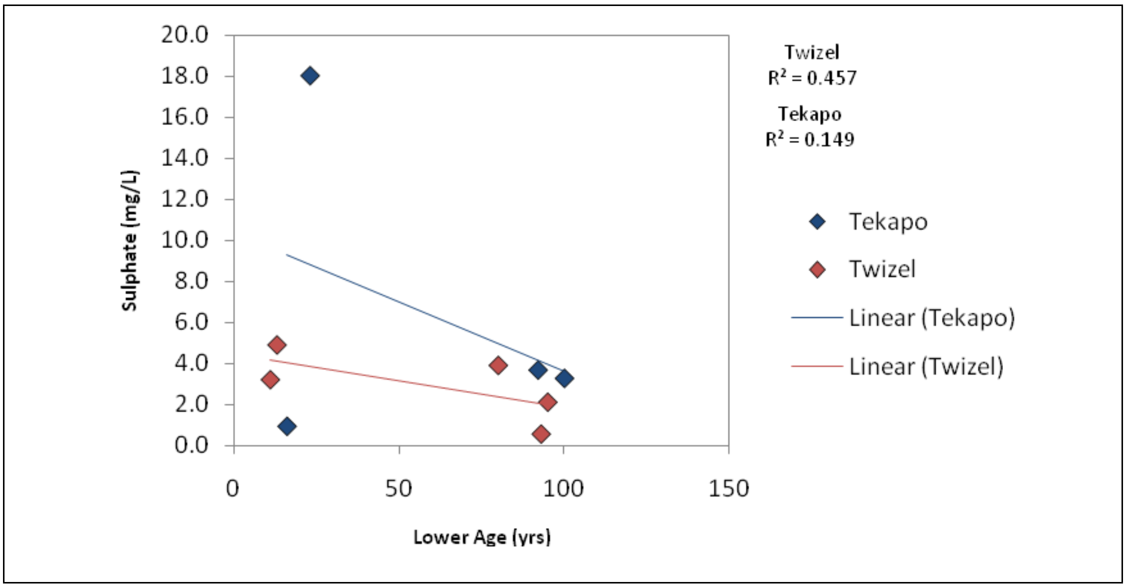


Figure 5: Lower groundwater age in comparison to sulphate concentrations.

Appendix 6A

Classification of Spring Morphology and Spring Type

Spring Classification

Spring Morphology

a) *Seepage* – discharge in which there is no observable point or source that the spring is flowing from

b) *Point Source* – describes a spring that is discharging from an observable point or source

c) *Linear/Channel* – discharge in which the spring is flowing along the length of a channel

d) *Horizon* – describes a springs that originate from a particular lithologic unit and can be followed along the length of that horizon

Spring Types

a) Artesian Spring – springs flowing freely above the land surface from an aquifer that is under artesian pressure

b) Sinkhole Spring – occur where karstic limestone caverns and shafts carrying subterranean water under artesian pressure intersects the land surface

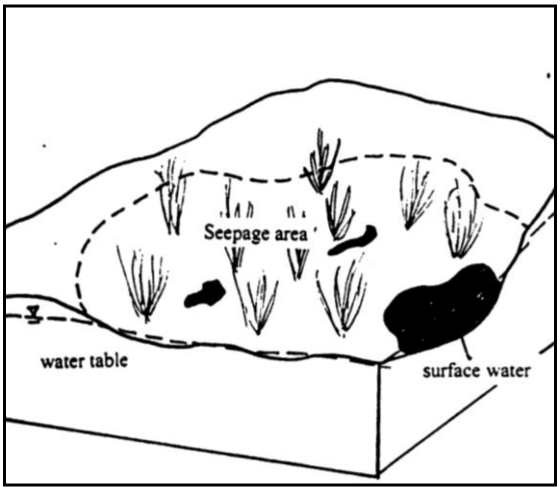
c) Joint/Fracture Spring – a spring that flows along a permeable zone caused by faulting and fracturing in a low-permeable rock unit. Spring discharge occurs when the fractures and joint intersect the land surface.

d) Fault Spring – formed when a permeable faulted unit is brought into contact with a less permeable unit, resulting in the formation of an impermeable boundary. The impermeable boundary forces the groundwater to flow along the fault plane to a more permeable zone where the spring is discharged

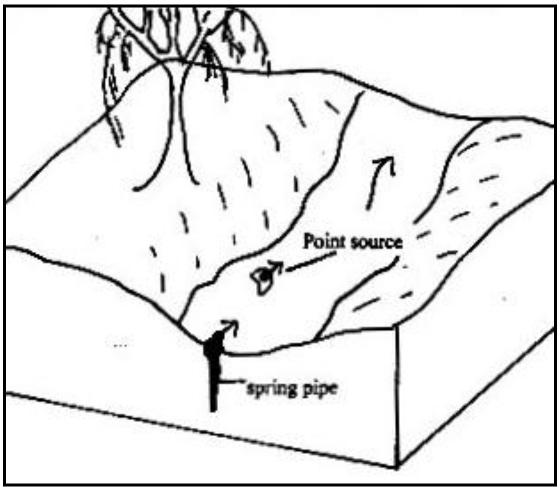
e) Contact Spring – forms when groundwater flowing in permeable formation comes into contact with underlying less permeable material

f) Depression Spring *– a spring that is formed when the water table intersects the land surface*

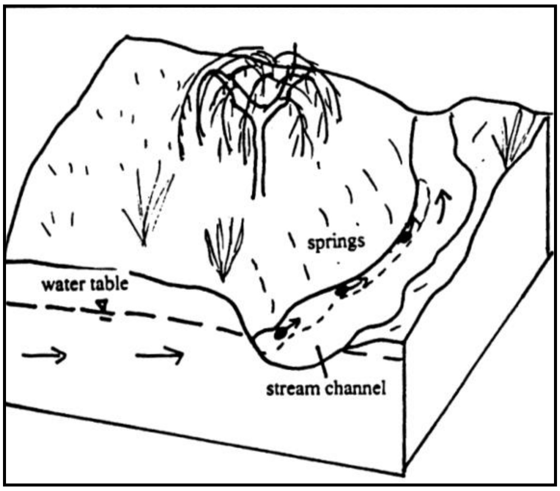
SPRING MORPHOLOGY



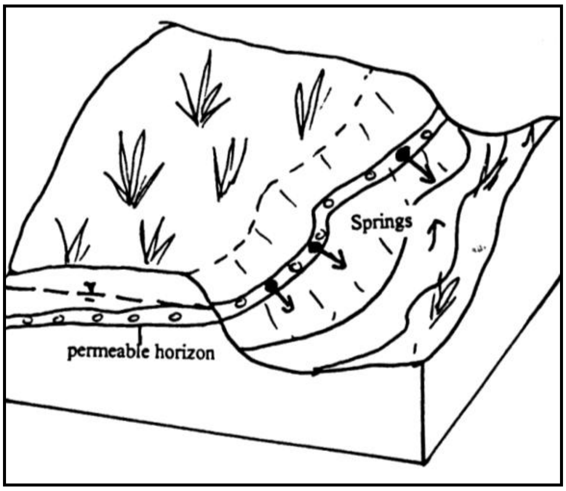
SEEPAGE



POINT SOURCE



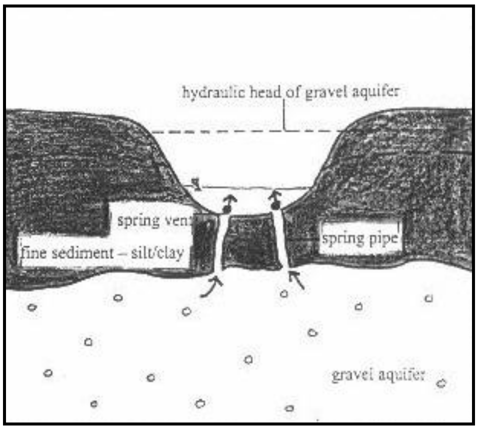
LINEAR/CHANNEL



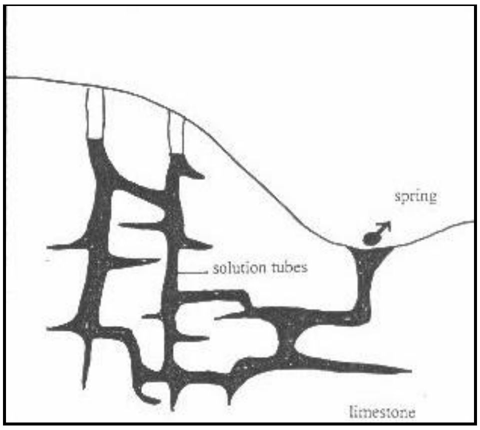
HORIZON

(Source: Earl, 1998)

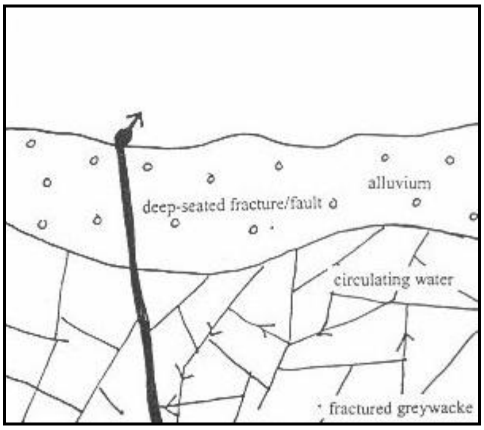
SPRING TYPES



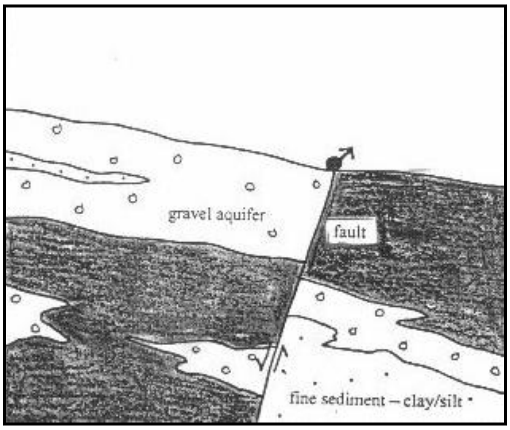
ARTESIAN



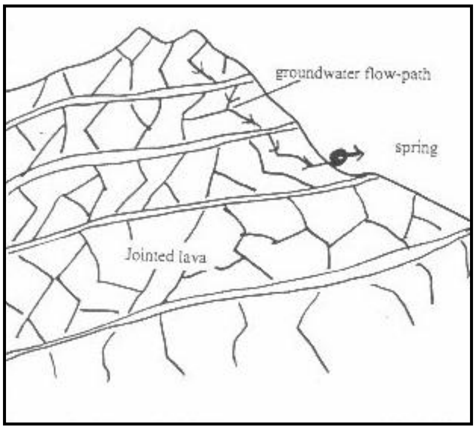
SINKHOLE



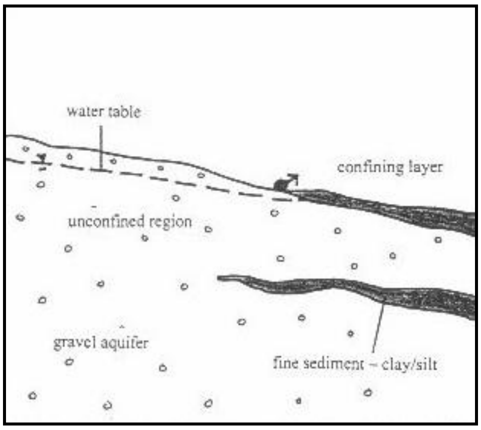
FRACTURE



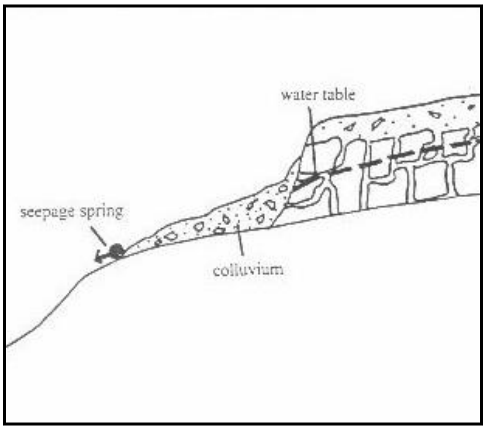
FAULT



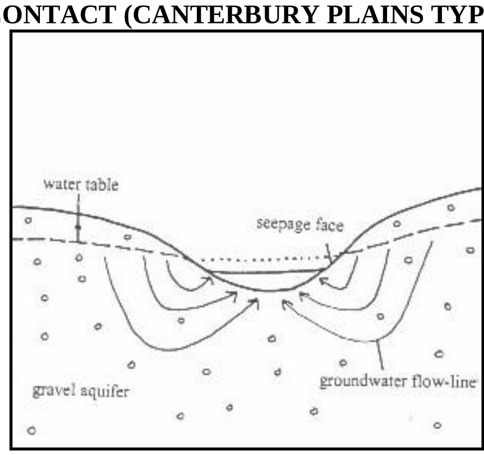
JOINT



CONTACT (CANTERBURY PLAINS TYPE)



CONTACT (BANKS PENINSULA TYPE)



DEPRESSION

(Source: Earl, 1998)

Appendix 6B

Summary of Spring Type and Morphology of Springs Located During This Study

Spring ID	Spring Type	Spring Morphology	Discharge Variability	Surface Geology
1	Fracture-Joint	Seepage	Permanent	Torlesse Bedrock
2	Depression	Point Source	Permanent	Alluvium
3	Depression or contact?	Seepage	Permanent	Tekapo Moraine/Alluvial Fan
4	Depression or contact?	Seepage	Permanent	Lake Beach Gravels
5	Depression or contact?	Seepage	Permanent	Lake Beach Gravels
6	Depression or contact?	Seepage	Permanent	Lake Beach Gravels
7	Depression or contact?	Seepage	Permanent	Lake Beach Gravels
8	Depression or contact?	Seepage	Permanent	Alluvial Fan
9	Depression or contact?	Seepage	Permanent	Lake Beach Gravels
10	Depression or contact?	Seepage	Permanent	Tekapo Moraine/Alluvial Fan
11	Depression or contact?	Seepage	Permanent	Tekapo Moraine/Alluvial Fan
12	Depression	Seepage	Permanent	Alluvium in Active Riverbed
13	Depression	Seepage	Permanent	Alluvium in Active Riverbed
14	Depression	Seepage	Permanent	Alluvium in Active Riverbed
15	Fracture-Joint	Seepage	Permanent	Balmoral Outwash Gravels/Torlesse Bedrock
16	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock
17	Fracture/Joint	Seepage	Permanent	Balmoral Outwash Gravels/Torlesse Bedrock
18	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock
19	Depression	Seepage	Permanent	Tekapo Outwash Gravels
20	Fracture/Joint	Seepage	Permanent	Tekapo Outwash Gravels
21	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock
22	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock/Alluvium
23	Fracture/Joint	Seepage	Permanent	Mt John Outwash Gravels/Torlesse Bedrock
24	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock
25	Depression	Seepage	Permanent	Balmoral Outwash Gravels/Alluvium
26	Depression	Seepage	Permanent	Alluvium in Active Riverbed
27	Depression	Seepage	Permanent	Alluvium in Active Riverbed
28	Depression	Seepage	Permanent	Alluvium in Active Riverbed
29	Depression	Seepage	Permanent	Alluvium in Active Riverbed
30	Depression	Seepage	Permanent	Alluvium in Active Riverbed
31	Depression	Seepage	Permanent	Alluvium in Active Riverbed
32	Depression	Seepage	Permanent	Alluvium in Active Riverbed
33	Depression	Seepage	Permanent	Alluvium
34	Depression	Seepage	Permanent	Alluvium
35	Depression	Seepage	Permanent	Alluvium
36	Depression	Seepage	Permanent	Alluvium
37	Depression	Seepage	Permanent	Alluvium
38	Depression	Seepage	Permanent	Alluvium in Active Riverbed
39	Contact	Horizon	Permanent	Alluvium in Active Riverbed

Spring ID	Spring Type	Spring Morphology	Discharge Variability	Surface Geology
40	Contact	Horizon	Permanent	Alluvium in Active Riverbed
41	Contact	Horizon	Permanent	Alluvium in Active Riverbed
43	Depression	Seepage	Permanent	Alluvium in Active Riverbed
44	Depression	Seepage	Permanent	Alluvium in Active Riverbed
45	Contact	Horizon	Permanent	Alluvium in Active Riverbed
46	Contact	Horizon	Permanent	Alluvium in Active Riverbed
47	Contact	Horizon	Permanent	Alluvium in Active Riverbed
48	Contact	Horizon	Permanent	Alluvium in Active Riverbed
49	Depression	Seepage	Permanent	Alluvium in Active Riverbed
50	Depression	Seepage	Permanent	Alluvium in Active Riverbed
51	Depression	Seepage	Permanent	Alluvium in Active Riverbed
52	Depression	Seepage	Permanent	Alluvium in Active Riverbed
53	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock
H38/0068	Depression	Point Source	Permanent	Alluvium in Active Riverbed
I37/0039	Unknown	Unknown	Unknown	Anthropogenic Deposits (Canal System)
I38/0019	Fracture/Joint	Seepage	Permanent	Torlesse Bedrock/Alluvial Fan

Appendix 6C

Photos of Springs Located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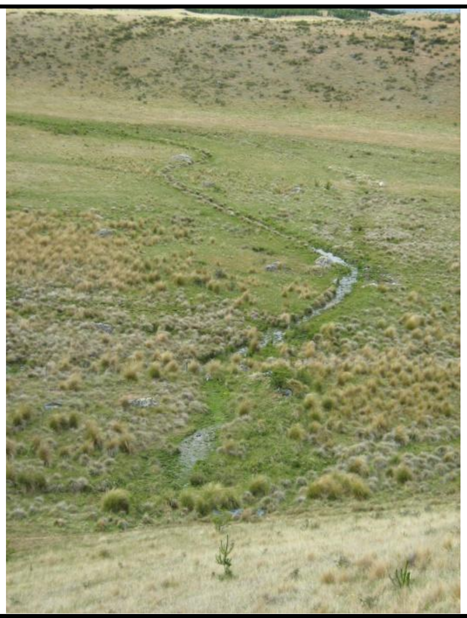

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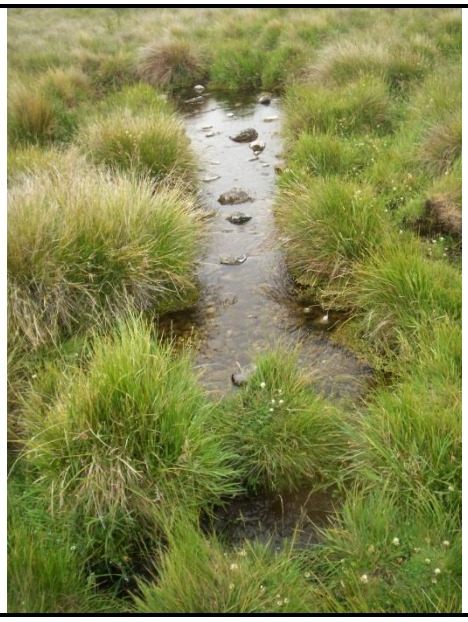

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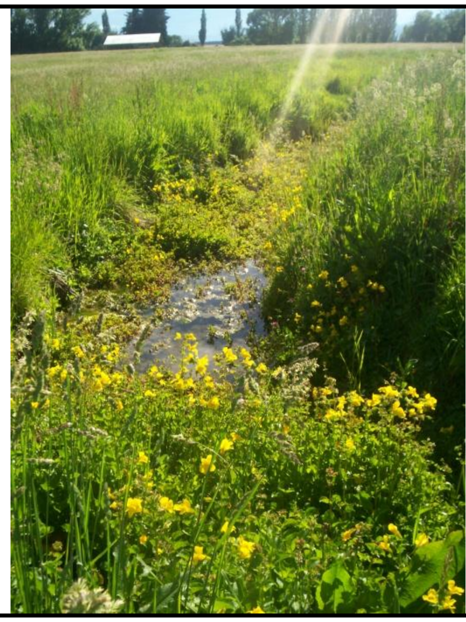

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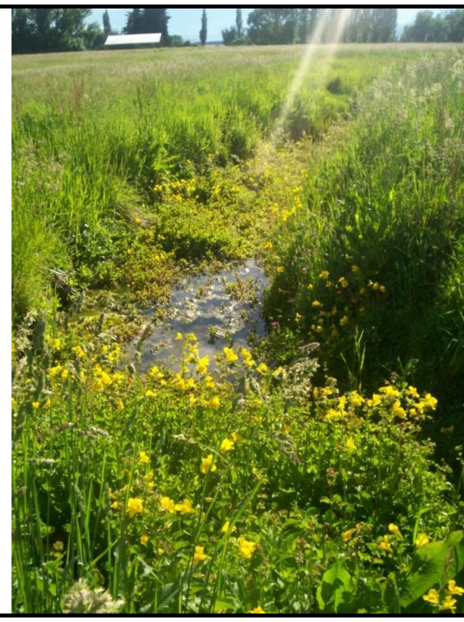


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H38/0068A


H38/0068B


H38/0068C


I38/0019

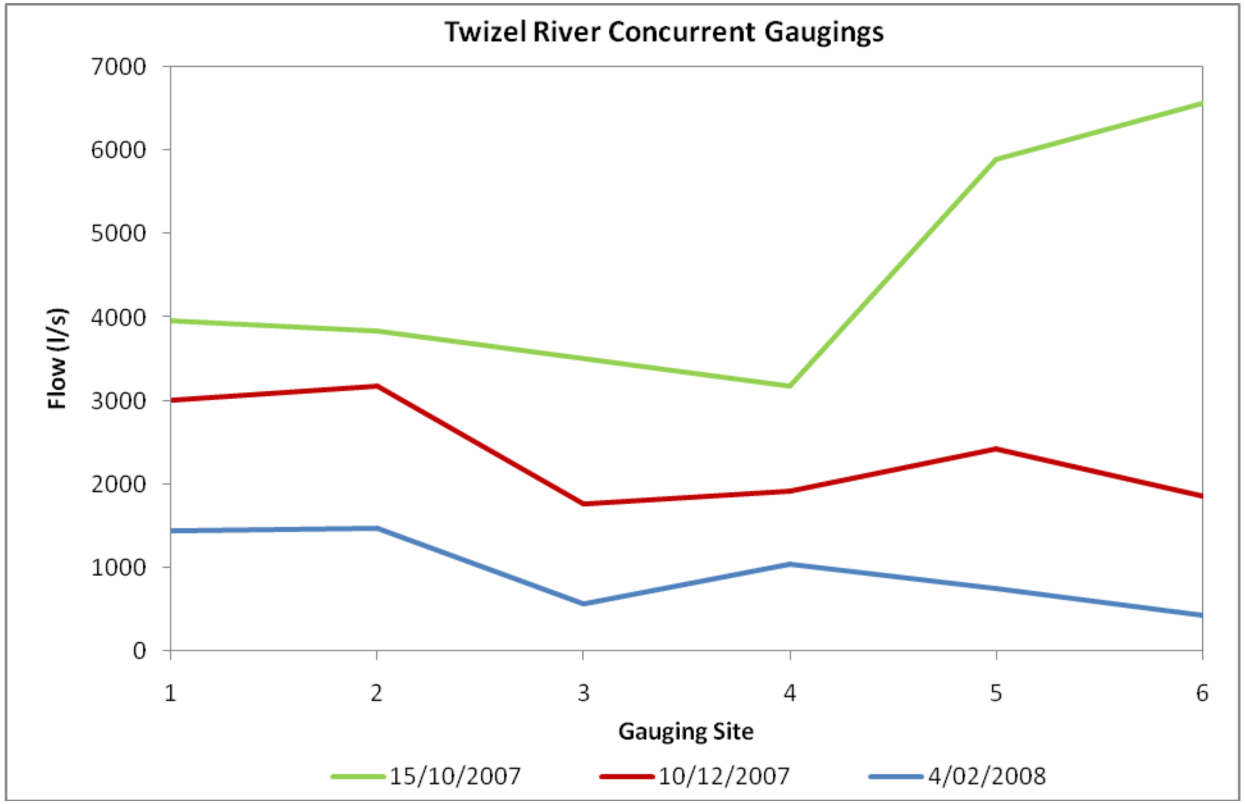
Appendix 6D

Historical and Current Flow Gauging Data

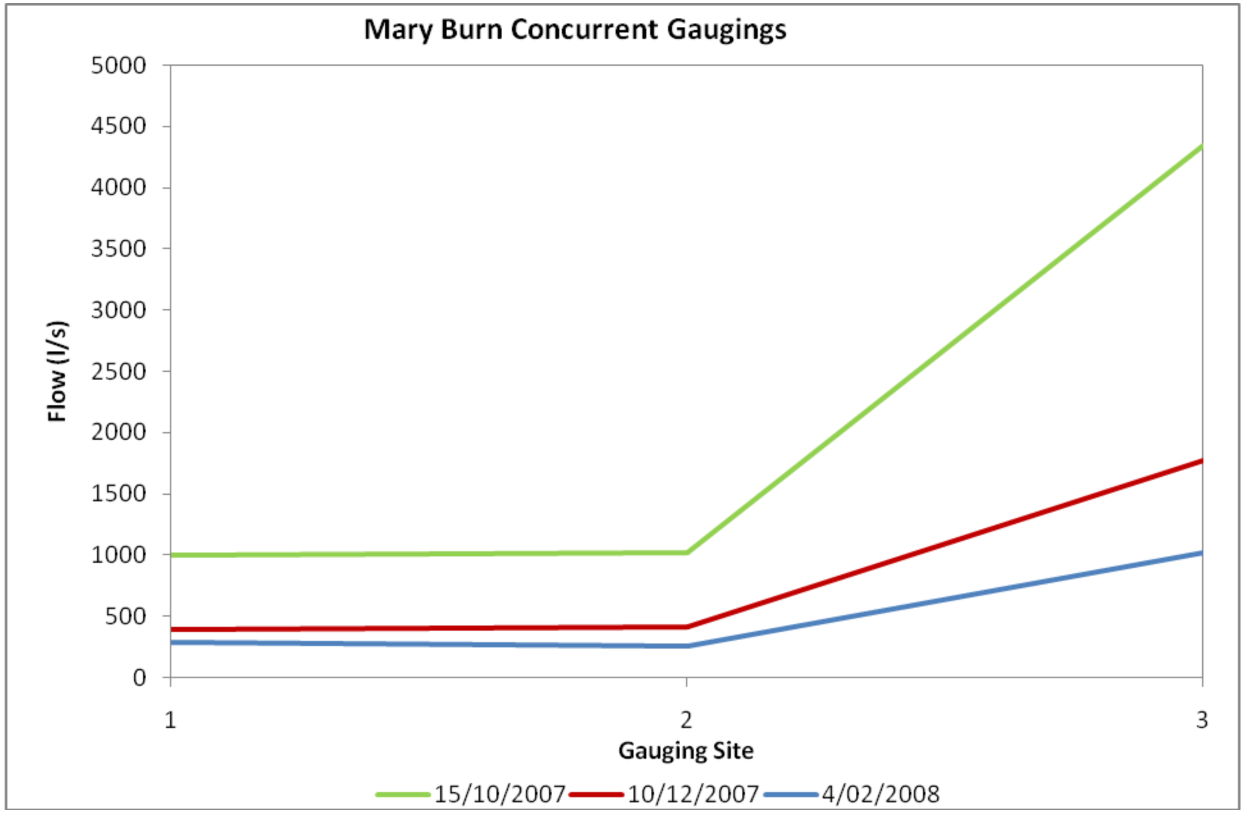
(see attached CD)

Appendix 6E

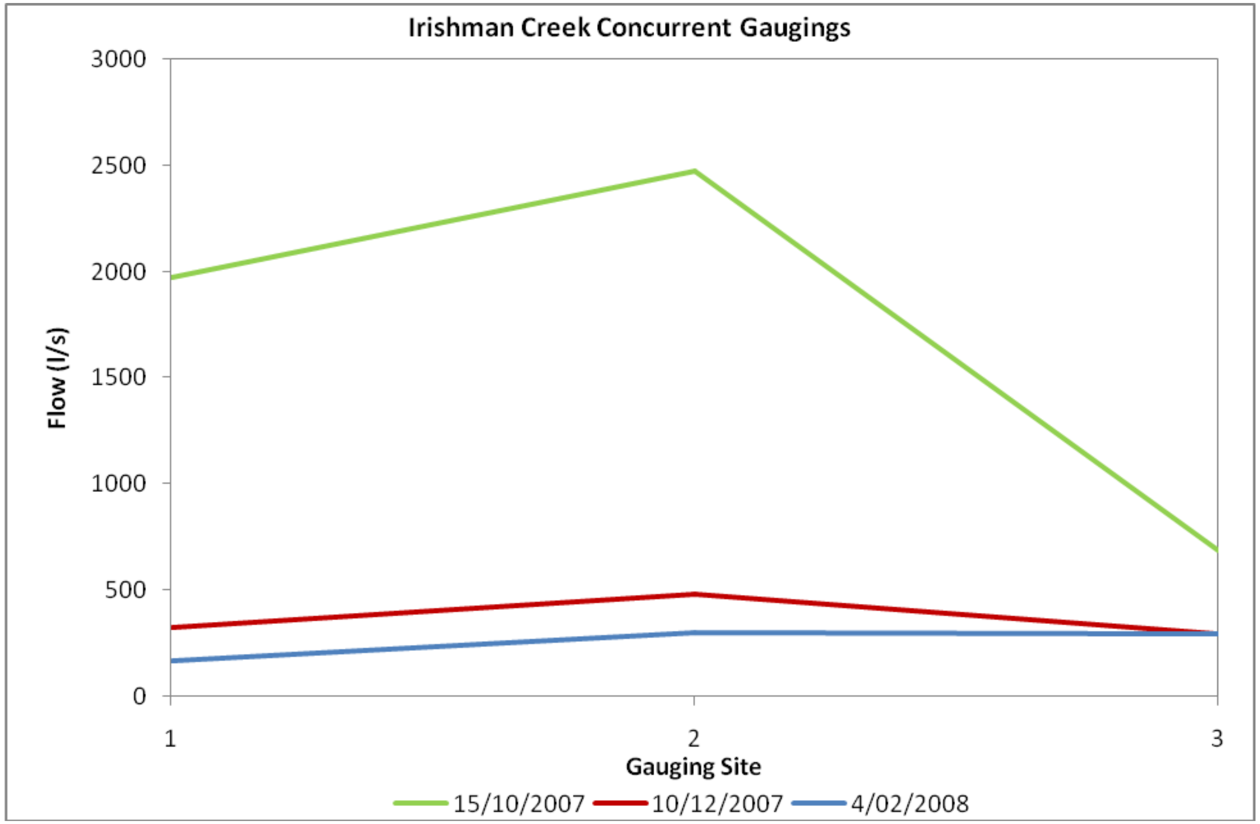
Concurrent Flow Gauging Graphs and Data



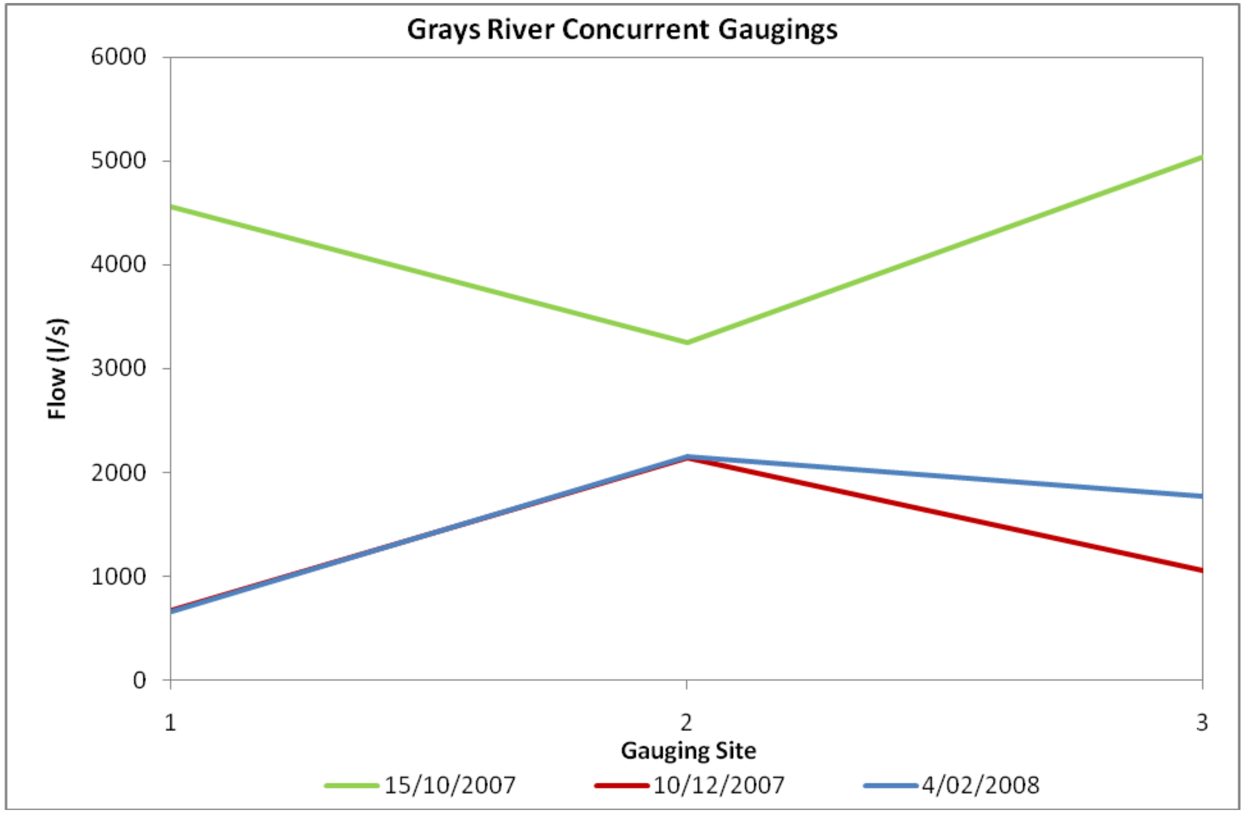
Site No.	Gauging Site	Measured Discharge (l/s)											
	Twizel River	15/11/2004			15/10/2007			10/12/2007			4/02/2008		
		Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)
T1	Twizel River #1	6248			3961			3004			1438		
T2	Twizel River #2	-	-	-	3835	-126	3	3180	+176	6	1476	+39	3
T3	Twizel River #3	-	-	-	-	-	-	1765	-1415	80	568	-908	160
T4	Twizel River #4	4221	-2027	48	3179	-656	21	1922	+157	8	1037	+468	45
T5	Twizel River #5	7409	+3188	43	5897	+2718	46	2418	+495	20	755	-282	37
T6	Twizel River #6	5943	-1466	25	6576	+679	10	1857	-561	30	435	-320	74



Site No.	Gauging Site	Measured Discharge (l/s)											
	Mary Burn	15/11/2004			15/10/2007			10/12/2007			4/02/2008		
		Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)
M1	Maryburn #1	262			998			391			283		
M2	Maryburn #2	364	+101	28	1018	+19	2	408	+17	4	255	-28.0	-11
M3	Maryburn #3	1767	+1403	79	4350	+3332	77	1768	+1360	77	1015	+761	75



Site No.	Gauging Site	Measured Discharge (l/s)											
	Irishman Creek	14/04/2004			15/10/2007			10/12/2007			4/02/2008		
		Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)
I1	Combined #1	317			1973			327			168		
I2	Combined #2	418	+101	24	2476	+503	20	480	+153	32	298	+131	44
I3	Irishman Creek #3	391	-27	7	686	-1790	261	296	-184	62	296	-2	1



Site No.	Gauging Site	Measured Discharge (l/s)								
	Grays River	15/10/2007			10/12/2007			4/02/2008		
		Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)	Flow (l/s)	Loss/Gain (l/s)	Loss/Gain (%)
G1	Combined	4554			679			665		
G2	Grays River #1	3251	-1303	40	2143	+1464	68	2156	+1492	69
G3	Grays River #2	5034	+1783	35	1050	-1093	104	1769	-388	22

Appendix 7A

Historical Bore Logs and Reports Located from Various Sources

(see attached CD)

Appendix 7B

Bore Logs in Environment Canterbury's Database for Wells within the Study Area

Borelog for well H38/0004

Gridref: H38:75921-59464 Accuracy : 2 (1=best, 4=worst)
Ground Level Altitude : 484.92 +MSD
Driller : Washingtons Exploration Ltd
Drill Method : Rotary/Percussion
Drill Depth : -11.1m Drill Date : 20/12/1997

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.40m	Brown silt and small gravel	
		-1.40m	Brown silty clay, small gravel	
		-2.09m	Brown silty clay small gravel, pebbles scattered	
	-2.55 HWL -3.80 LWL	-4.80m	Brown silty clay, gravels, pebbles cobbles	
-5		-6.69m	Brown silty clay, gravels, pebbles, cobbles, dribble of water	
		- 10.0m	Brown silty-sandy Grey pebbles and gravels. Water	
-10		- 11.1m	As above, test 20 litres, 10 seconds.	

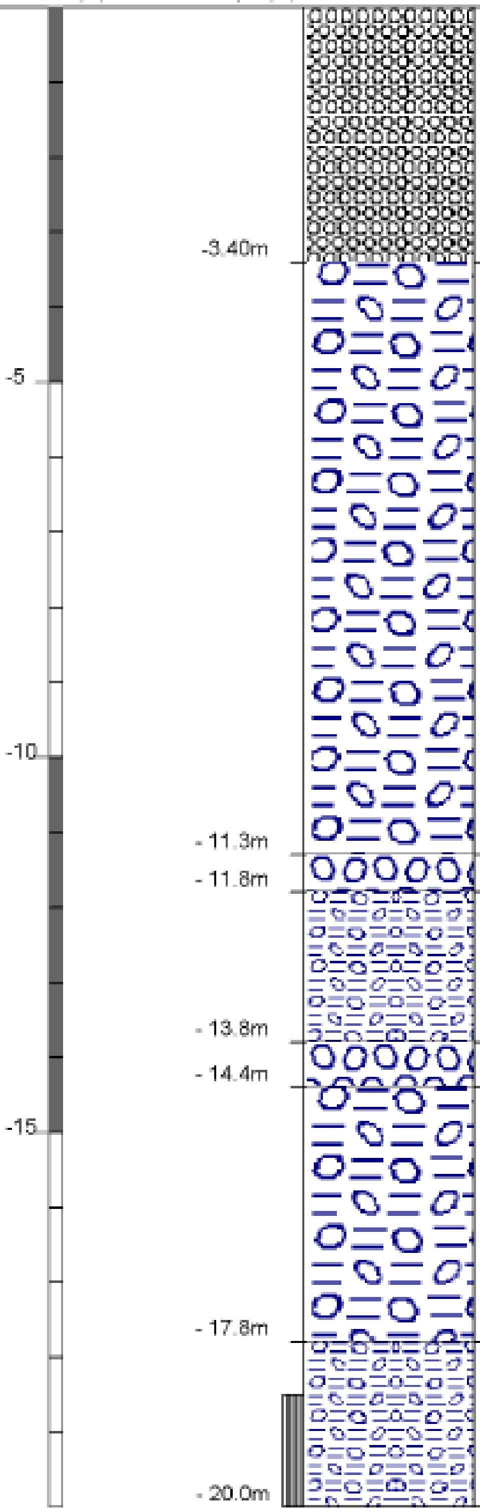
Borelog for well H38/0005

Gridref: H38:8093-6483 Accuracy : 4 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary/Percussion
Drill Depth : -20.2m Drill Date : 28/08/1998

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
			Claybound gravel	
-5		-5.30m	Greywacke boulder	
		-5.80m	Claybound gravel and cobbles	
		-9.00m	Cobbley claybound Water-bearing gravel	
-10		- 12.8m	Fine Water-bearing gravel & clay	
		- 13.5m	Greywacke Water-bearing boulder	
		- 14.3m	Cobbley claybound Water-bearing gravel	
-15		- 18.3m	Fine Water-bearing gravel	
-20		- 20.2m		

Borelog for well H38/0006

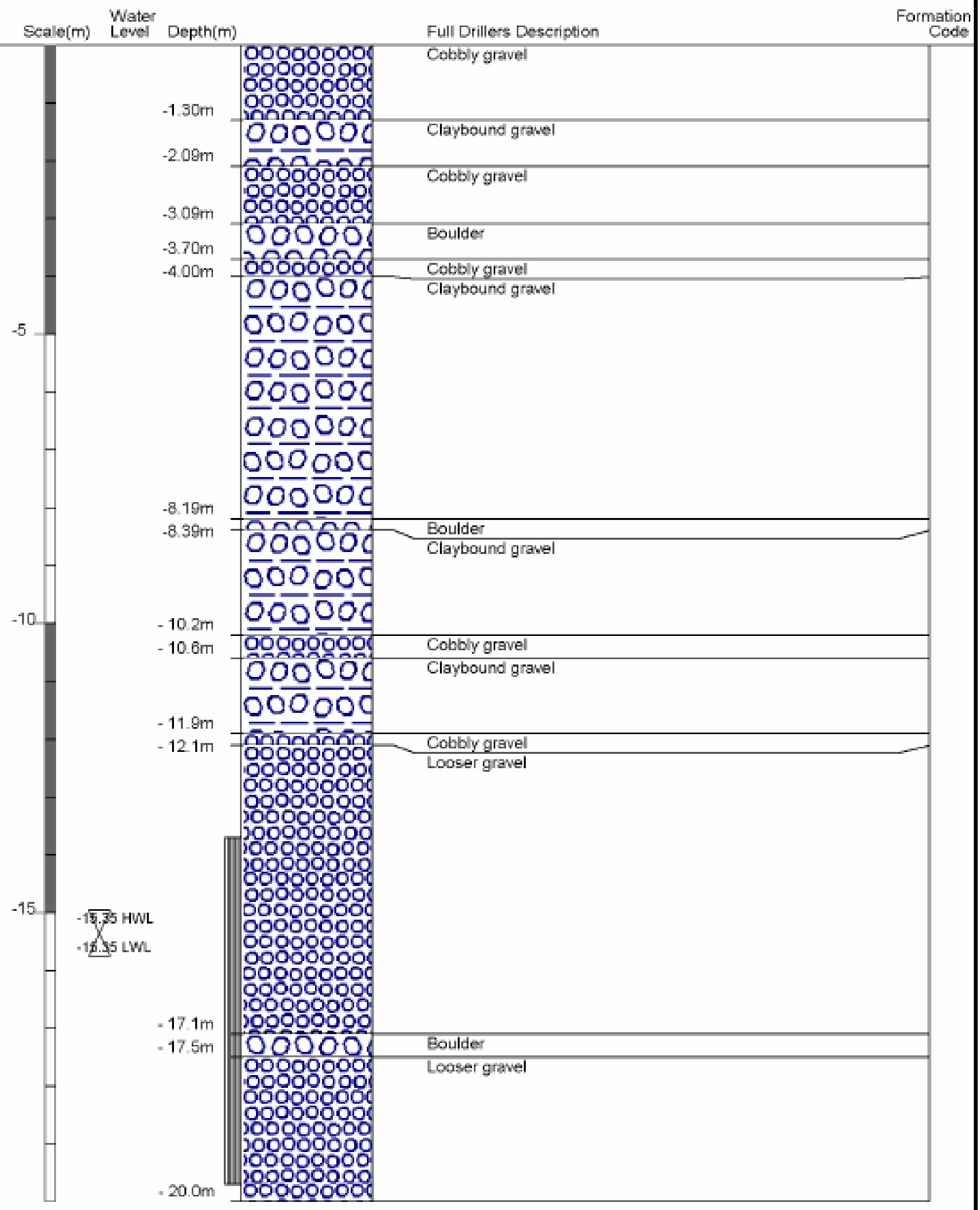
Gridref: H38:8105-6475 Accuracy : 4 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary/Percussion
Drill Depth : -20m Drill Date : 28/08/1998



Depth(m)	Full Drillers Description	Formation Code
0 – -3.40m	Loose small gravel	
-3.40m – -11.3m	Cobbley claybound gravel	
-11.3m – -11.8m	Greywacke boulders	
-11.8m – -13.8m	Fine gravel & clay - wet sample	
-13.8m – -14.4m	Greywacke boulders	
-14.4m – -17.8m	Cobbley claybound gravel	
-17.8m – -20.0m	Fine gravel & clay with some cobbles	

Borelog for well H38/0007

Gridref: H38:78325-55738 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 461.88 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary Rig
Drill Depth : -20m Drill Date : 6/04/1999



Borelog for well H38/0008

Gridref: H38:78279-55593 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 462.69 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary Rig
Drill Depth : -22.5m Drill Date : 7/04/1999

Water Level: -16.43 HWL, -16.89 LWL

Depth(m)	Full Drillers Description	Formation Code
-1.10m	Loose gravel	
-2.50m	Cobbly gravel	
-3.00m	Boulder	
-4.80m	Cobbly gravel	
-7.19m	Claybound gravel	
-7.59m	Boulders	
- 11.7m	Claybound gravel	
- 12.9m	Cobbly gravel	
- 14.0m	Claybound gravel	
- 14.5m	Cobbly gravel	
- 21.3m	Claybound gravel	
- 21.6m	Cobbly gravel	
- 22.5m	Claybound gravel	

Scale(m): -5, -10, -15, -20

Borelog for well H38/0009 page 1 of 2

Gridref: H38:78095-55453 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 462.05 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary Rig
Drill Depth : -21m Drill Date : 1/08/2000

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-1.00m	Gravely sand moist Yellow/Brown sand and gravel with some silt. 50% gravel, diameter 5-20mm 30-40% sand (medium-coarse)	
		-2.00m	Sandy gravel, moist Yellow/Brown sand and gravel with some silt. 70% gravel 60% between 2-8mm remainder <10mm 30% sand	
		-4.00m	Gravely sand, moist Yellow/Brown sand and gravel with some silt 60% gravel diameter 5-20mm 30-40% sand medium-coarse.	
-5		-6.00m	Sandy gravel, moist Yellow/Brown sand and gravel with some silt 70% gravel 60% between 2-8mm remainder < 10mm, increasing angularity 30% sand	
		-7.00m	Sandy gravel, moist Grey/Yellow/Brown sandy gravel with some silt 75% gravel 35% 2-5mm 55% 10-15mm < 20% sand	
		-8.00m	Sandy gravel, moist Grey/Yellow/Brown sandy gravel with some silt, 80% gravel 35% 2-5mm, 55% 10-15mm > 30% sand	
		-9.00m	Sandy gravel, moist Grey/Yellow/Brown sandy gravel with eom silt, 65% gravel 35% 2-5mm, 55% 10-15mm > 30% sand	
-10		- 10.0m	Sandy gravel moist Grey/Yellow/Brown sand and gravel with some silt 70% gravel 60% between 2-8m remainder < 10mm increasingly angular 30% sand. Slow digging possible went through a boulder	
		- 11.0m	Sandy gravel moist Grey/Yellow/Brown sandy gravel with some silt 65% gravel 35% 2-5mm, 55% 10-20mm, < 20% sand	

Borelog for well H38/0009 page 2 of 2

Gridref: H38:78095-55453 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 462.05 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary Rig
Drill Depth : -21m Drill Date : 1/08/2000

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		- 11.0m	Sandy gravel moist Grey/Yellow/Brown sandy gravel with some silt 65% gravel 35% 2-5mm, 55% 10-20mm, < 20% sand	
-15		- 15.0m	Sandy gravel, moist Grey/Yellow/Brown becoming more Grey between 13-14m sandy gravel with some silt. 65% gravel 35% 2-5mm, 55% 10-15mm > 30% sand	
	-15.81 HWL -15.81 LWL	- 18.0m	Sandy gravel, moist Grey/Brown sandy gravel with some silt, 65% gravel 35% 2-5mm, 55% 10-15mm > 30% sand. Increasing angularity between 16-17m suggests a boulder	
-20		- 20.0m	Sandy gravel, wet, Grey/Yellow gravel with some sand and silt trace, silt washed out in water 80% gravel 80% 2-20mm, 10% sand	
		- 21.0m	Gravel, wet Grey/Yellow/Brown gravel with some silt and sand, 80% gravel, 40% 2-5mm 60% 10-25mm	

Borelog for well H38/0010

Gridref: H38:77403-55034 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 470.73 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Tubex
Drill Depth : -30.55m Drill Date : 2/09/2000

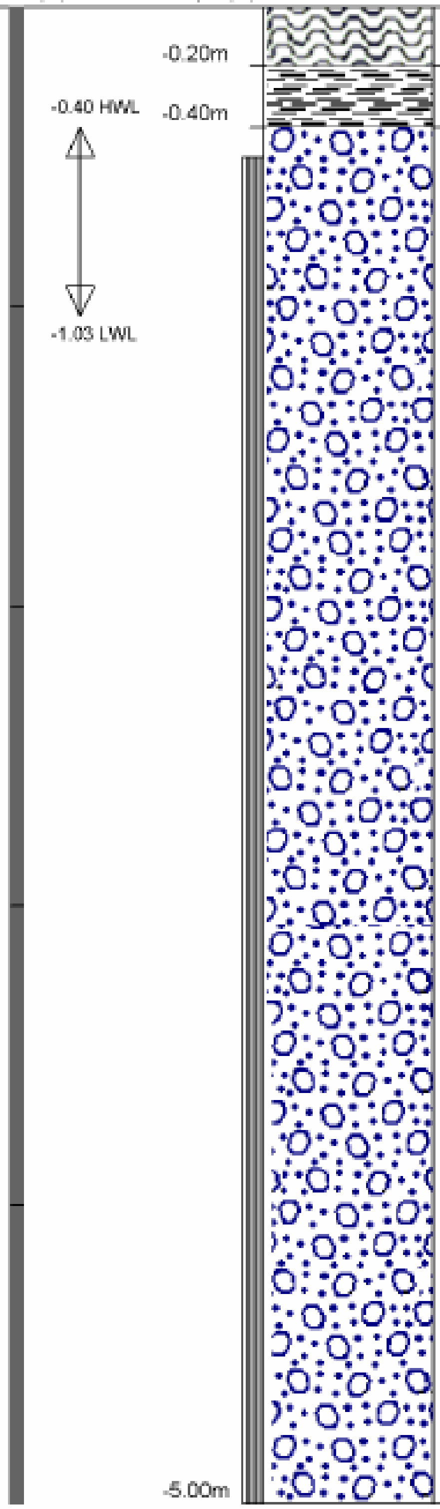
Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.20m	Topsoil	
		-1.80m	Cobbley Greywacke gravel and silts	
		-2.60m	Fine gravel	
		-3.20m	Fine gravel and silt	
		-3.50m	Greywacke cobbles	
		-4.00m	silts and fine gravel	
-5		-5.30m	Cobbley gravel	
		-7.00m	Finer gravel and silt	
		-8.80m	Fine gravel and cobbles	
-10		- 12.5m	Coarser gravels and silts	
		- 14.0m	Finer gravel and silt	
-15		- 17.0m	Fine gravel silt and some cobbles	
-20		- 20.2m	Fine gravel and silt	
	-21.50 HWL -21.73 LWL	- 24.5m	Claybound gravel and cobbles	
-25 -30		- 30.6m	Course gravels	

Borelog for well H38/0012

Gridref: H38:77924-59271 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 471.08 +MSD
Driller : not known
Drill Method : Machine Dug
Drill Depth : -5m Drill Date : 8/08/2000

Scale(m)	Water Level	Depth(m)		Full Drillers Description	Formation Code
		-0.20m		Black soil	
	-0.40 HWL	-0.40m		Grey clay - subsoil	
	-1.03 LWL	-5.00m		Grey - mix of gravels, sand, cobbles - old fluvial deposits	



Borelog for well H38/0013

Gridref: H38:75169-58386 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 496.8 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Null
Drill Depth : -21m Drill Date : 31/08/2000

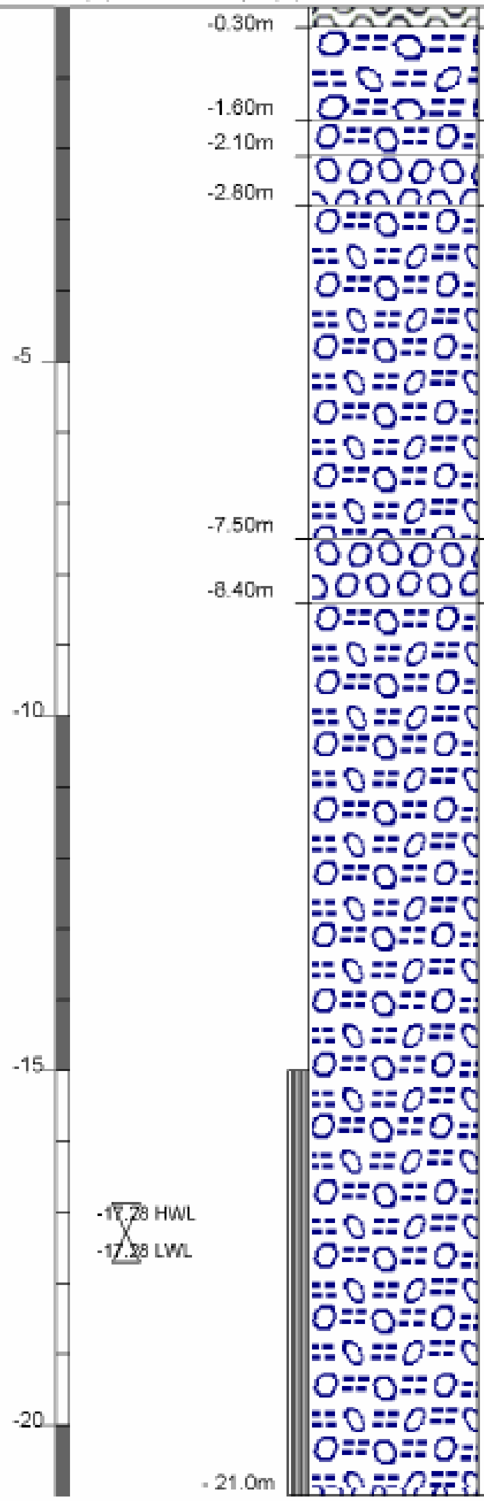
Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.60m	Topsoil fine sand	
		-2.40m	Sandy gravel	
		-3.10m	Silty Greywacke cobbles	
-5		-5.80m	Silts and Greywacke gravels	
		-9.00m	Silty Greywacke gravels and cobbles	
		-9.40m	Boulder	
-10		- 13.6m	Silty gravels	
-15		- 15.6m	Dry silty gravels	
-20	-17.51 HWL -19.17 LWL	- 21.0m	Silty gravels and some cobbles	

Borelog for well H38/0015

Gridref: H38:77125-57945 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 481 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Null
Drill Depth : -21m Drill Date : 31/08/2000

Depth(m)	Full Drillers Description	Formation Code
-0.30m	Topsoil	
-1.60m	Silty gravels and cobbles	
-2.10m	Silty gravels	
-2.80m	Boulder	
-7.50m	Silty gravels and some cobbles	
-8.40m	Cobbley gravels	
- 21.0m	Silty gravels	



Borelog for well H38/0016

Gridref: H38:76730-56096 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 476.63 +MSD
Driller : McNeill Drilling Co. Ltd
Drill Method : Null
Drill Depth : -30m Drill Date : 2/09/2000

Water Level: -25.84 HWL, -26.45 LWL

Depth(m)	Full Drillers Description	Formation Code
0 to -6.60m	Silty gravels	
-6.60m to -7.10m	Cobbley gravels	
-7.10m to -21.8m	Silty gravels and cobbles	
-21.8m to -22.3m	Boulder	
-22.3m to -24.0m	Silty gravels - hole dry	
-24.0m to -30.0m	Silty gravels - water at 25m	

Borelog for well H38/0035

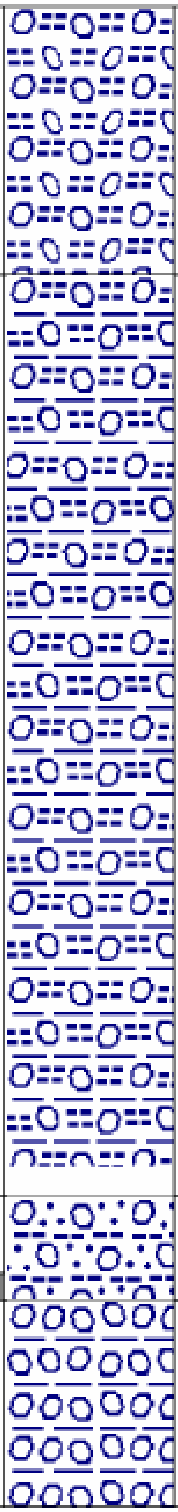
Gridref: H38:85614-51852 Accuracy : 2 (1=best, 4=worst)
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -118.7m Drill Date : 20/07/2002

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.40m	Earth	
		-1.70m	Sandy gravels, odd large one	
		-4.50m	Sandy grey gravels	
-10			Sandy claybound gravels	
-20		- 20.4m	Some water stained grey/brown gravels and sand	
		- 26.9m	Freeish water stained grey gravels and sand	
-30		- 34.0m	Free water stained gravels and sand	
		- 37.5m	Free water stained gravels and sand	
-40				
-50				
-60		- 62.8m	Free water stained gravels some sand	
-70				
-80		- 87.2m	Free water stained gravels and sand	
-90				
-100				
-110		- 113.8m	Sandy claybound gravels	
		- 118.7m		

Borelog for well H38/0038

Gridref: H38:7893-6860 Accuracy : 3 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Tubex
Drill Depth : -42m Drill Date : 4/07/2002

Environment Canterbury
Your regional council



Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
-5, -10		-7.50m	Silty gravel, cobbles & boulders	
-10, -15, -20, -25, -30		- 33.3m	Yellow silty claybound gravel, boulders - damp	
-35		- 36.2m	Silty sandy gravel	
-40		- 42.0m	Yellow heavy claybound gravel	

Borelog for well H38/0039

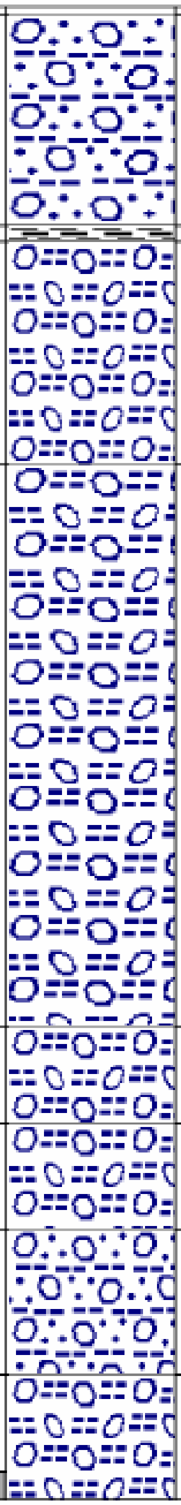
Gridref: H38:76841-55858 Accuracy : 4 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Tubex
Drill Depth : -40.8m Drill Date : 11/04/2003

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-2.30m	Sandy gravels and boulders	
-5, -10, -15, -20		- 20.6m	Damp silty sandy gravels some boulders	
-25		- 27.8m	Silty sandy gravels and cobbles	
-30, -35		- 37.2m	Very silty sandy gravels	
-40		- 40.8m	Looser silty sandy gravels	

Borelog for well H38/0041

Gridref: H38:7682-5603 Accuracy : 4 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Tubex
Drill Depth : -36.9m Drill Date : 14/04/2003

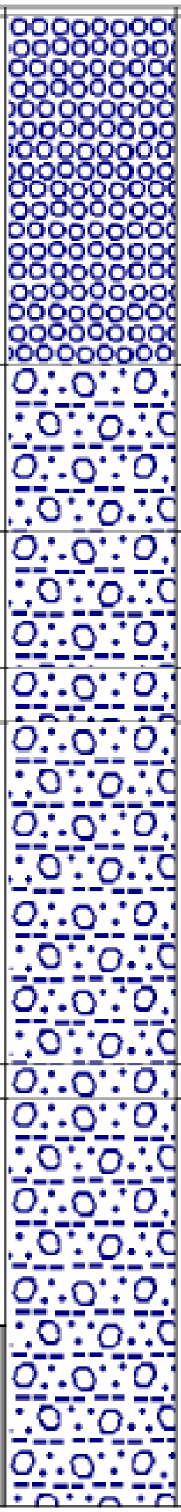


Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.20m	Topsoil	
-5		-5.40m	silty sandy gravel & boulders	
		-5.80m	yellow clay	
-10		- 11.3m	damp silty gravels	
-15, -20, -25		- 25.2m	silty gravel, some cobbles	
		- 27.6m	cleaner silty gravel	
-30		- 30.2m	heavy silt-bound gravel	
		- 33.8m	very silty sandy gravel	
-35		- 36.9m	loose silty gravel & cobbles	

Borelog for well H38/0044

Gridref: H38:7556-5775 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -65.8m Drill Date : 27/01/2004

Scale(m) -10, -20, -30, -40, -50, -60



Depth(m)	Full Drillers Description	Formation Code
-0.40m	Topsoil, medium/large grey angular gravels	
- 15.7m	Small-medium grey gravels, rounded	
- 23.0m	Yellow silt, grey coarse sand, medium/large brown and grey rounded gravels, moist	
- 29.0m	Yellow silt, grey and brown sand, medium/large brown and grey gravels, 20 l/sec	
- 31.4m	Yellow silt, brown and grey sand, medium/large brown and grey gravels, 20 l/sec	
- 46.4m	Brown silt, brown and grey sand, medium/large brown angular gravels, 20 l/sec	
- 47.9m	Brown silt, coarse brown sand, medium/large brown angular gravels, 3.3 l/sec	
- 65.8m	Brown silt, sand, medium / large angular gravels	

Borelog for well H38/0045

Gridref: H38:7523-5668 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -71m Drill Date : 30/10/2003

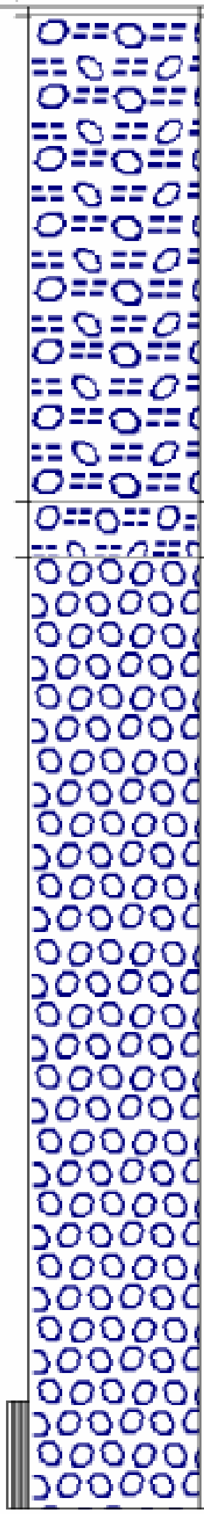
Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.70m	Topsoil, large grey gravels, boulders	
-10		- 11.8m	Small/medium grey gravels	
		- 18.9m	Medium/large brown and grey gravels	
-20		- 26.2m	Brown silty clay - fine grey sand, medium/large grey gravels	
-30		- 37.6m	Grey and brown sand - coarse, medium/large grey gravels - dry	
-40		- 47.0m	Yellow silt, brown and grey sand, medium/large brown and grey gravels, traces of quartz - moist	
-50, -60		- 65.0m	Yellow silt, brown and grey sand, medium/large grey gravels, 2.5 l/sec, and at 59m 20 l/sec.	
-70		- 71.0m	Yellow silt, grey and brown sand, medium/large brown and grey gravels, hard rock, test 20 l/sec, constant good flow	

Borelog for well H38/0047

Gridref: H38:7620-5645 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -65m Drill Date : 6/11/2003

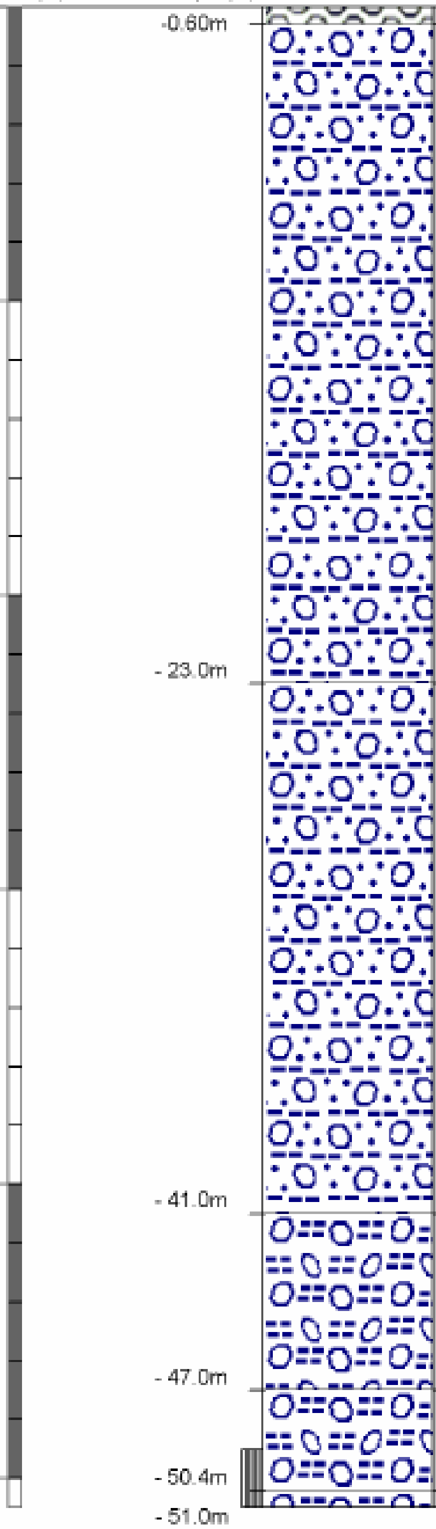
Environment Canterbury
Your regional council



Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.40m	Topsoils, brown silty brown and grey gravels, pebbles	
-10			Brown silty brown and grey gravels, pebble, cobbles, boulders	
-20		- 21.4m		
		- 23.8m	Brown silty brown and grey gravels	
-30			Brown silty grey gravels, pebbles, cobbles	
-40				
-50				
-60		- 65.0m		

Borelog for well H38/0048

Gridref: H38:7252-5872 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -51m Drill Date : 1/12/2003



Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.60m	Topsoil	
-10, -20		- 23.0m	Yellow silty sands medium / large grey gravels, moist	
-30, -40		- 41.0m	Yellow brown silt small sand content medium / large grey brown gravels, dry	
		- 47.0m	Yellow brown silt medium / large brown gravels angular, dribble water	
-50		- 50.4m	Yellow silt medium / large brown and grey angular gravels, water 20 litres / 4 -5 seconds	
		- 51.0m	~~Brown silt medium / large brown gravels, water 20 litres /~~	

>> *description did not fit on this page.*

Borelog for well H38/0049

Gridref: H38:7022-5759 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -83m Drill Date : 19/12/2003

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.60m	Topsoil big rocks	
		-7.80m	Small / medium gravels yellow silt	
-10, -20, -30		- 36.7m	Yellow silt brown sands medium /large grey gravels, moist	
-40		- 44.2m	Brown silty clays medium / large grey gravels, damp	
-50		- 57.8m	Yellow silt medium / large grey gravels	
-60		- 65.0m	Brown silty clays medium / large gravels, damp	
-70		- 77.0m	Yellow silt medium / large grey gravels, dribble water	
-80		- 83.0m	Yellow silt grey sand medium / large grey gravels dribble water. Water test 20 litres / 17 seconds. 20 litres / 7 - 8 seconds	

Borelog for well H38/0050

Gridref: H38:6589-5551 Accuracy : 4 (1=best, 4=worst)
Driller   : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth   : -41m   Drill Date : 8/12/2003

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.50m	Topsoil and rocks	
-5		-6.70m	Yellow silt grey sand medium large brown gravels	
-10, -15, -20, -25		- 25.0m	Brown silt grey sand medium large brown gravels moist	
		- 27.8m	Blue silt blue sands coarse dribble water	
-30, -35, -40		- 41.0m	Blue silt blue sands small medium rounded gravels. Water test 20 litres / 6 seconds	

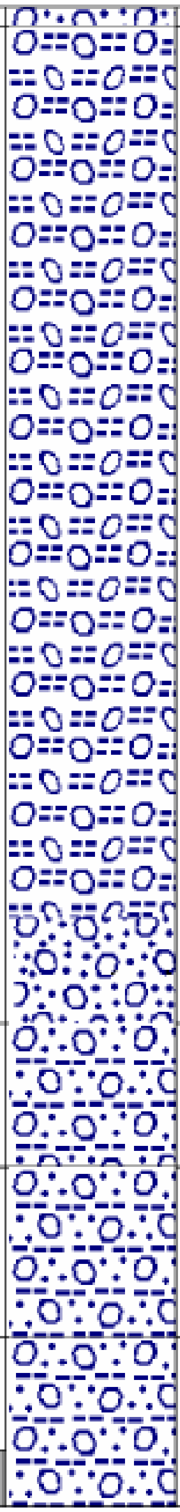
Borelog for well H38/0051

Gridref: H38:76618-55816 Accuracy : 2 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -41m Drill Date : 6/01/2004

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.60m	Topsoil round grey rocks	
-5		-7.80m	Yellow silt small / medium grey gravels	
-10, -15		- 18.6m	Yellow silt grey sand medium / large angular grey gravels	
-20		- 23.4m	Brown silt grey sand medium / large rounded gravels	
-25, -30		- 31.6m	Brown silt grey sand small / medium grey gravels	
-35		- 35.0m	Whitish brown silt grey sand medium / large grey gravels - moist	
-40		- 41.0m	Whitish brown silt grey sands coarse , medium / large grey gravels. Water test - 20 litres / 5 - 6 seconds	

Borelog for well H38/0052

Gridref: H38:6545-5517 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -53m Drill Date : 15/12/2003

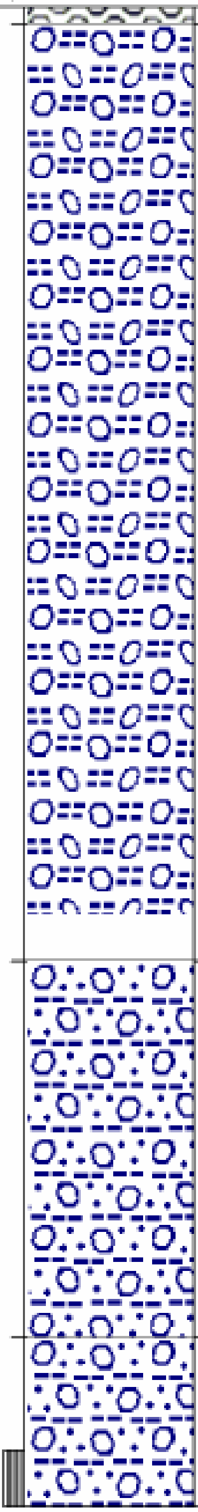


Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.70m	Topsoil and medium rocks	
-10, -20, -30		-35.9m	Yellow silt grey gravels - medium /large dry	
-40		- 41.0m	Blue sands light brown silt medium / large grey gravels moist	
		- 47.0m	Blue sands light brown silt medium / large grey gravels dribble	
-50		- 53.0m	Blue sands light brown silt medium / large grey gravels. Water test - 20 litres / 10 seconds. 20 litres / 5 seconds	

Borelog for well H38/0053

Gridref: H38:6584-5548 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -53m Drill Date : 11/12/2003

Environment Canterbury
Your regional council



Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.60m	Topsoil, rocks	
-10, -20, -30		- 33.7m	Yellow silt grey gravels - damp	
-40		- 47.0m	Brown silt blue sands medium large grey gravels dribble water. Water test at 41.0m 20 litres / 10-12 seconds. Water test at 47.0m 20 litres / 6-7 seconds	
-50		- 53.0m	Brown silt blue sand medium large gravels. Water test at 53.0m 20 litres / 6 seconds	

Borelog for well H38/0056

Gridref: H38:7155-5879 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -95m Drill Date : 13/01/2004

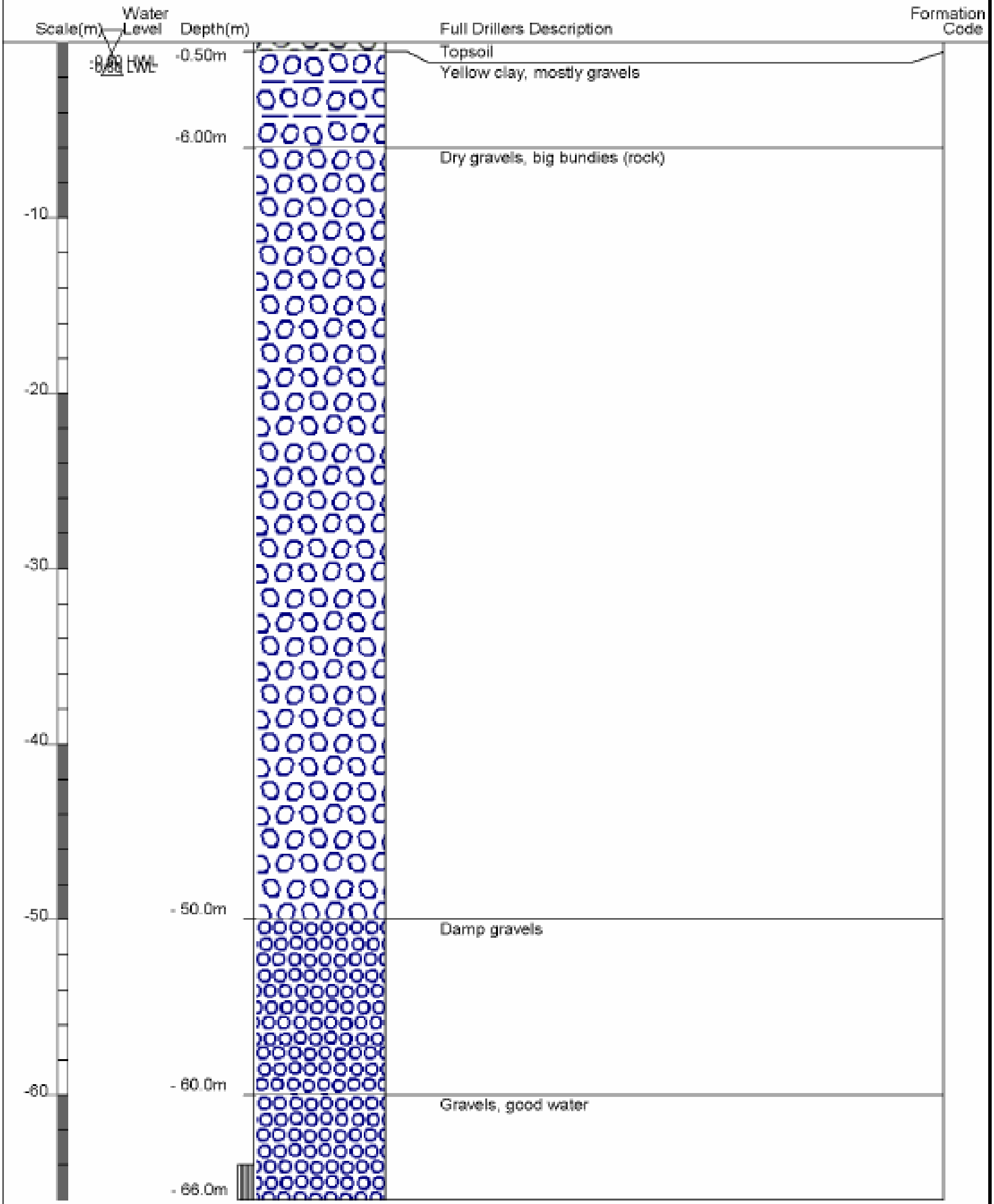
Environment Canterbury
Your regional council

Scale(m): -10, -20, -30, -40, -50, -60, -70, -80, -90

Water Level	Depth(m)	Full Drillers Description	Formation Code
	-0.60m	Topsoil large boulders	
	-7.80m	Small grey gravels- Dry	
	- 16.7m	Medium large brown gravels - moist, boney	
	- 65.0m	Brown silty sand medium large brown gravels, boulders damp	
	- 76.3m	Brown silty sand medium large brown and grey gravels , boulders ,moist dribble water	
	- 95.0m	Yellow silt medium large grey angular gravels, Water 20 litres / 10 seconds	

Borelog for well H38/0057

Gridref: H38:7256-5768 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -66m Drill Date : 19/11/2003



Borelog for well H38/0058

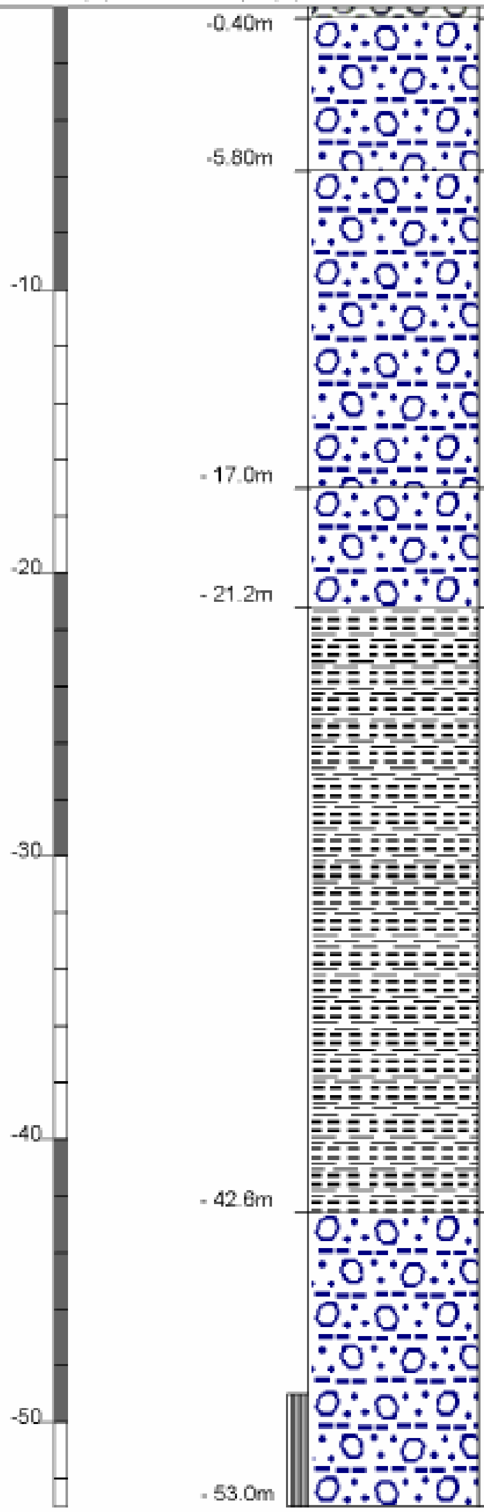
Gridref: H38:6915-5729 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -90m Drill Date : 24/11/2003

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.50m	Topsoil	
-10, -20, -30, -40, -50, -60		- 66.0m	Brown-grey gravels, big bundies (rocks)	
		- 68.0m	Gravels	
-70		- 78.0m	Grey-Brown gravels, big big bundies	
-80		- 90.0m	Wet gravels, bundies	

Borelog for well H38/0059

Gridref: H38:6844-5664 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -53m Drill Date : 27/11/2003

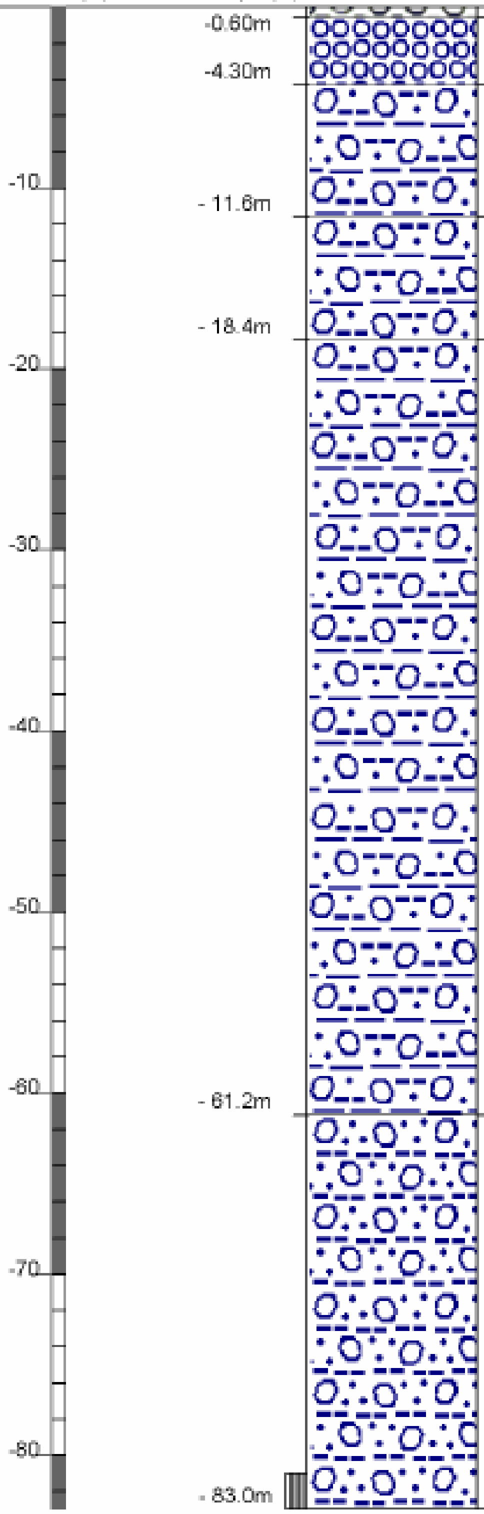


Water Level	Depth(m)	Full Drillers Description	Formation Code
		Topsoil, large boulders	
	-0.40m	Yellow silt, grey sand, medium/large brown gravels	
	-5.80m	Brown silt, sand, medium/large brown and grey gravels - moist	
	- 17.0m	Brown silt-sand, medium/large brown gravels, water 0.9l/sec	
	- 21.2m	Blue silty clay pug	
	- 42.6m	White silt, Blue sand, coarse, small/medium blue gravels, pump test 1.25 l/sec	
	- 53.0m		

Borelog for well H38/0060

Gridref: H38:70742-57234 Accuracy : 3 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -83m Drill Date : 12/01/2004

Environment Canterbury
Your regional council



Depth(m)	Full Drillers Description	Formation Code
-0.60m	Topsoil	
-4.30m	Medium large angular grey gravels	
- 11.6m	Brown silty clay brown sand medium large grey angular gravels	
- 18.4m	Brown silty clay brown sand small medium grey angular gravels	
- 61.2m	Brown silty clay brown sand medium large grey angular gravels	
- 83.0m	Brownish yellow silt brown and grey sand medium large angular gravels Moist Water tests 72.0m 20l / 20 sec , 77.0m 20l / 11-12 sec and 83.0m 20l / 8 -9 sec	

Borelog for well H38/0061

Gridref: H38:7769-5883 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -17m Drill Date : 15/01/2004

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-2.20m	Topsoil small grey gravels	
-5		-11.0m	Grey silt grey sand small medium grey rounded gravels moist. Water test at 5.0m 20 l / 12 secs	
-10				
-15		- 17.0m	Grey silt grey sand small medium grey rounded gravels. Water test at 17.0m 20 l / 6 secs	

Borelog for well H38/0063

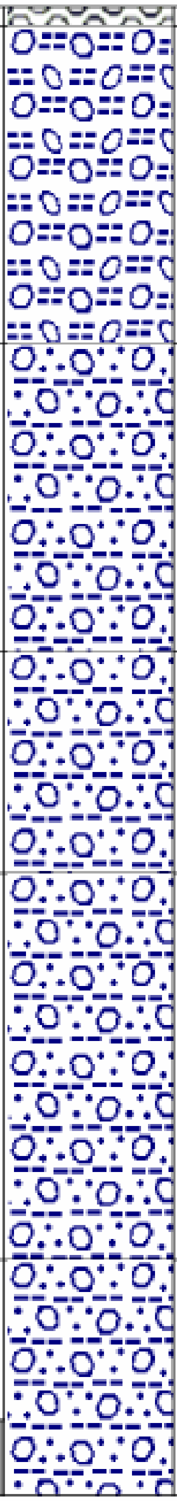
Gridref: H38:7840-6812 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -48m Drill Date : 14/02/2004

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.70m	Topsoil large boulders	
		-2.30m	Large boulders yellow silt	
-5		-8.60m	Yellow silt grey sand small medium gravels	
-10, -15		- 17.7m	Brownish yellow clay small grey and brown gravels	
-20		- 23.9m	Brownish orange silt medium large grey gravels dribble water	
-25, -30		- 30.4m	Brown silt medium large angular gravels. Water test 20l / 15 sec	
-35		- 38.0m	Brownish yellow silt small medium angular gravels. Water test 20l / 9 -10 sec	
-40, -45		- 48.0m	Brown sandy gravels, small water	

Borelog for well H38/0064

Gridref: H38:7699-5515 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -39m Drill Date : 3/02/2004

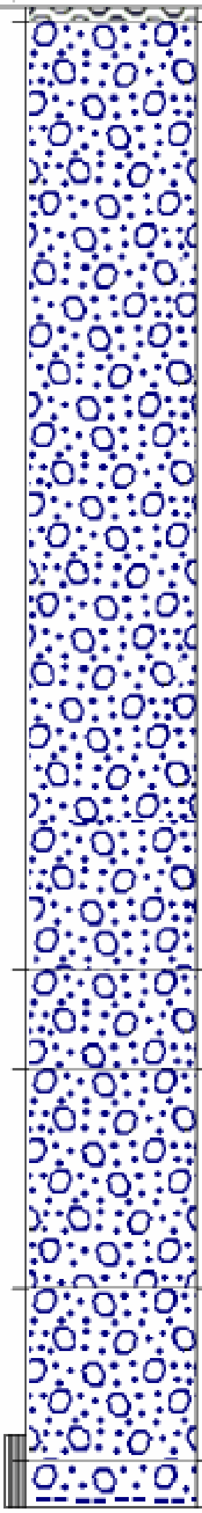


Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.50m	Topsoil grey rocks	
-5		-8.80m	Yellow silt small medium grey gravels	
-10, -15		- 16.9m	Yellow silt grey sand small medium grey angular gravels	
-20		- 22.7m	Brown silt grey sand medium large grey rounded gravels	
-25, -30		- 32.8m	Yellow silt grey sand medium large grey angular gravels moist	
-35		- 39.0m	Yellowish white silt grey sand medium large grey angular gravels. Water - 20 l/ 10 secs. Water test 20 l /6 -7 secs	

Borelog for well H38/0065

Gridref: H38:7681-5597 Accuracy : 3 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -41m Drill Date : 7/10/2005

Environment Canterbury
Your regional council



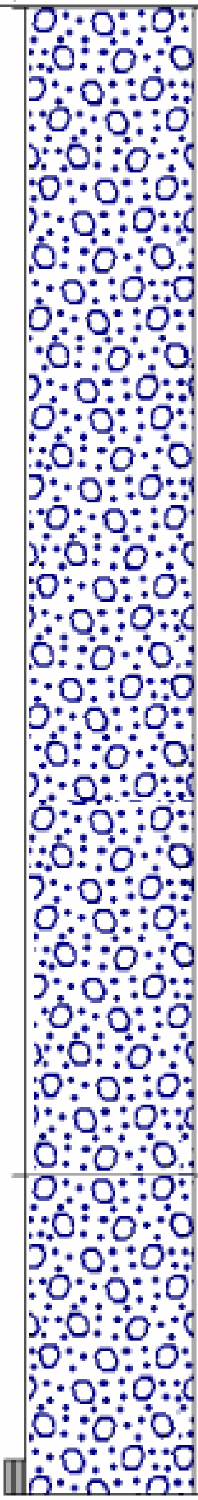
Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.40m	topsoil	
-5, -10, -15, -20, -25			grey sands, med/large grey gravels	
		- 26.3m	grey sands, med/large grey gravels - moist	
-30		- 29.0m	grey sands, med/large grey gravels - dribble	
-35		- 35.0m	grey sands, med/large grey gravels - 20L/ 15 sec's	
-40		- 39.7m	yellow silt, brown sands, brown tight gravels, 20L/ 5-6 sec's	
		- 41.0m		

Borelog for well H38/0066

Gridref: H38:7658-5573 Accuracy : 5 (1=best, 4=worst)
Driller : Well Drilling Direct
Drill Method : Rotary/Percussion
Drill Depth : -42m Drill Date : 18/02/2006

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.05m	topsoil	
-5, -10, -15, -20, -25, -30			sand, stone shingle	
-35, -40		- 33.0m	water-bearing sand stone shingle	
		- 42.0m		

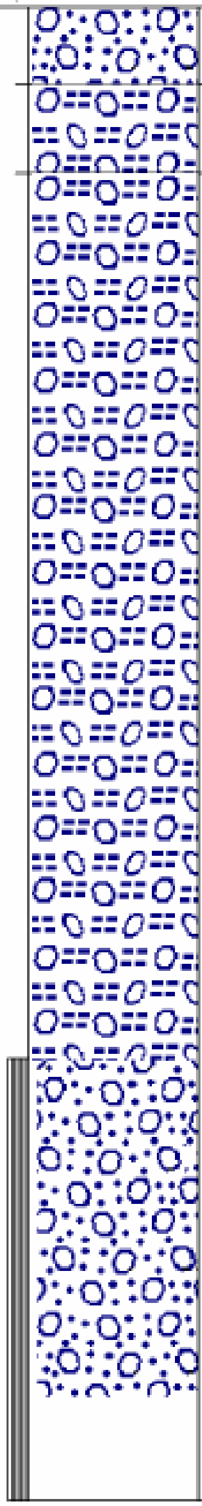


Borelog for well H38/0069

Gridref: H38:78488-57034 Accuracy : 2 (1=best, 4=worst)
Driller : CW Drilling and Investigation
Drill Method : Hollow Stem Auger
Drill Depth : -13.5m Drill Date : 14/12/2004

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.70m	sandy gravel, fine coarse gravels, some cobbles, coarse sands	
		-1.50m	silty gravel, fine-coarse gravel, grey silt	
-5			silty gravel, fine-coarse gravel, some cobbles, light grey silt	
-10		- 13.5m		



Borelog for well H38/0070

Gridref: H38:77700-53700 Accuracy : 3 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary/Percussion
Drill Depth : -19.87m Drill Date : 2/03/2005

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.10m	light brown silty fine sand; loose dry (Loess)	
		-3.00m	bluish grey medium gravels, minor fine and coarse gravels; dense, dry. clasts are rounded psammitic greywacke and semischist. at 1.5m trace sand and silt (fluvioglacial fan gravels)	
-5		-7.50m	silty medium to coarse gravels, minor cobbles, dense, damp	
		-8.50m	silty sandy coarse gravels and cobbles, dense, damp	
-10, -15		- 15.0m	silty medium to coarse gravels, trace cobbles; dense, dry, silt adhears to recovered clasts. clasts are psammitic greywacke and semischist with rare pelitic greywacke and semischist. rods wet below 13.7m	
		- 16.5m	coarse gravels-cobbles, some silt; dense, wet, clasts are well rounded	
		- 17.0m	fine to coarse gravel, some silt; dense, wet	
		- 19.9m	medium to coarse gravel, minor silt; dense, wet	

Borelog for well H38/0185

Gridref: H38:7972-5975 Accuracy : 3 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -23m Drill Date : 15/10/2005

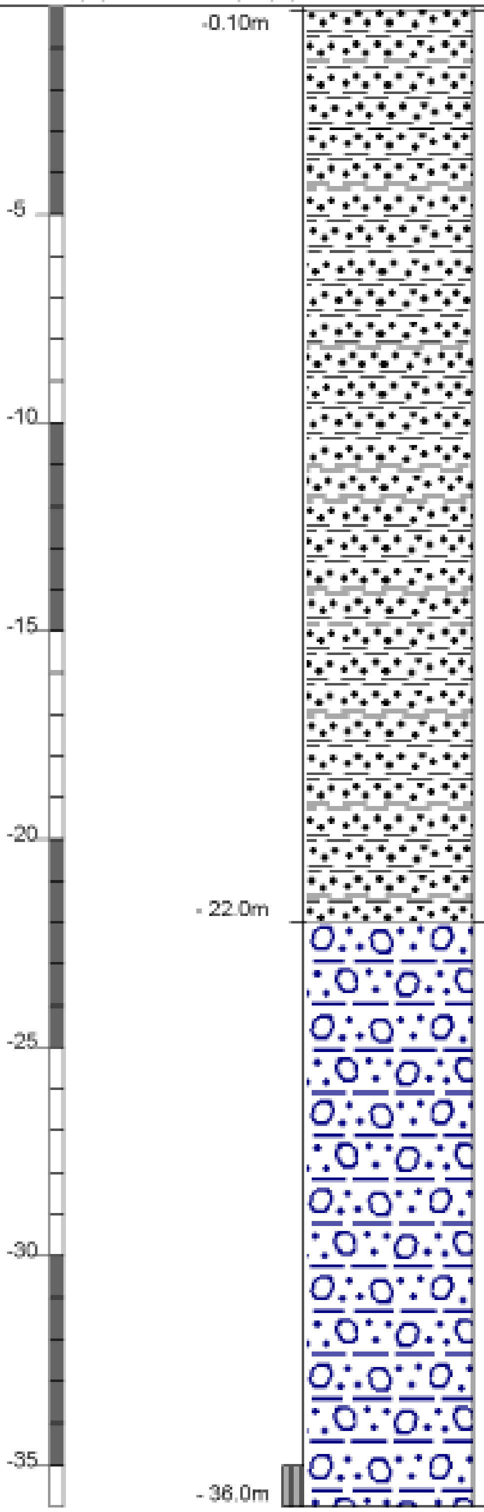
Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.60m	Topsoil, rocks	
-5		-5.00m	yellow silt, grey sand, large boulders	
-10		- 11.0m	yellow silt, grey sand, large boulders - dribble water	
-15		- 17.0m	yellow silt, grey sand, large boulders - 20L/20sec	
-20		- 23.0m	yellow silt, grey sand, large boulders - 20L/4-5sec	

Borelog for well H38/0188

Gridref: H38:6807-5655 Accuracy : 5 (1=best, 4=worst)
Driller : Well Drilling Direct
Drill Method : Rotary Rig
Drill Depth : -36m Drill Date : 10/12/2006

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.10m	Topsoil	
			Sand & Clay	
		- 22.0m	Shingle sand & clay	
		- 36.0m		



Borelog for well H38/0206

Gridref: H38:8050-6618 Accuracy : 5 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -108.5m Drill Date : 23/11/2006

Environment Canterbury
Your regional council

Depth(m)	Full Drillers Description	Formation Code
-1.00m	topsoil	
- 42.0m	yellow mustard colour rock & grey gravels	
- 48.0m	big rocks - damp from 38.5m to 45.4m but no H2O	
- 60.0m	clay bound brown gravels	
- 69.5m	wet clay, some stones	
- 72.0m	soft wet clay, sand, some brown stones	
- 73.7m	running sand, small gravels	
- 78.0m	green fawn soft wet mud, some stones	
- 82.7m	green fawn silty sandy clay, some stones	
- 86.0m	silty clay, sandy gravels - damp	
- 90.0m	silty sandy gravels - damp	
- 94.0m	running sandy gravels (5mm in size), small H2O	
- 99.0m	grey-brown rusty gravels, dribble H2O	
- 103.5m	rusty brown gravels, some sand - air lifting 2Lps - 1500RPM High air - 40min to clean H2O	
- 106.5m	running gravels, very small (5mm in size) - not much H2O	
- 108.5m	brown rusty gravels, some sandy clay - air lifting 4.5Lps - 1250RPM High air	

Scale(m): -10, -20, -30, -40, -50, -60, -70, -80, -90, -100

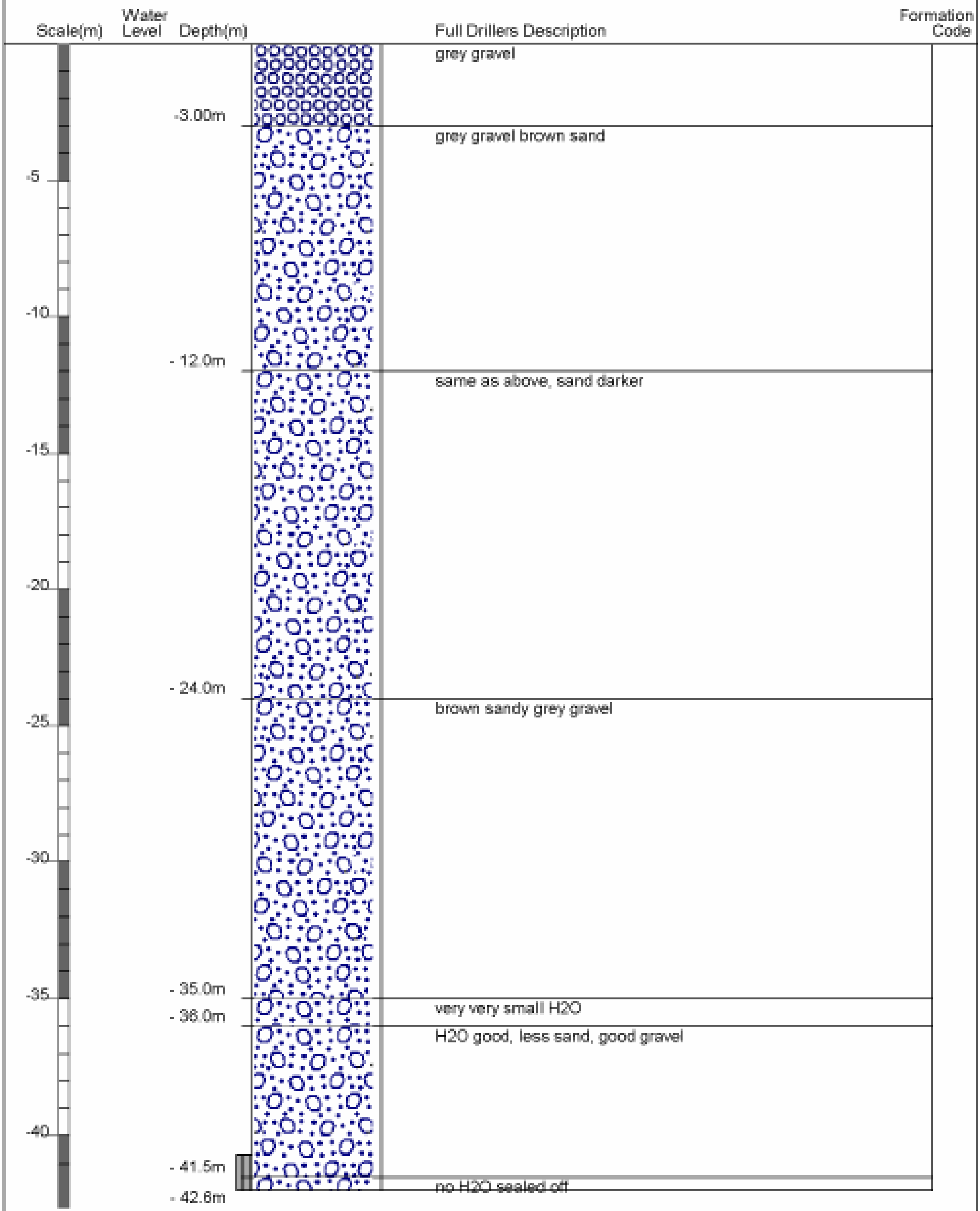
Borelog for well H38/0220

Gridref: H38:77608-58236 Accuracy : 2 (1=best, 4=worst)
Driller : Barber Drilling Pty Ltd
Drill Method : Rotary Rig
Drill Depth : -17m Drill Date : 18/04/2007

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.30m	brown topsoil	
		-3.00m	grey dusty sandy boulder with gravels	
		-4.50m	grey damp dusty sandy boulders with gravels	
-5			grey hard puggy claybound gravels and boulders	
-10				
-15		- 15.5m		
		- 17.0m	yellow puggy claybound gravels with water	

Borelog for well H38/0221

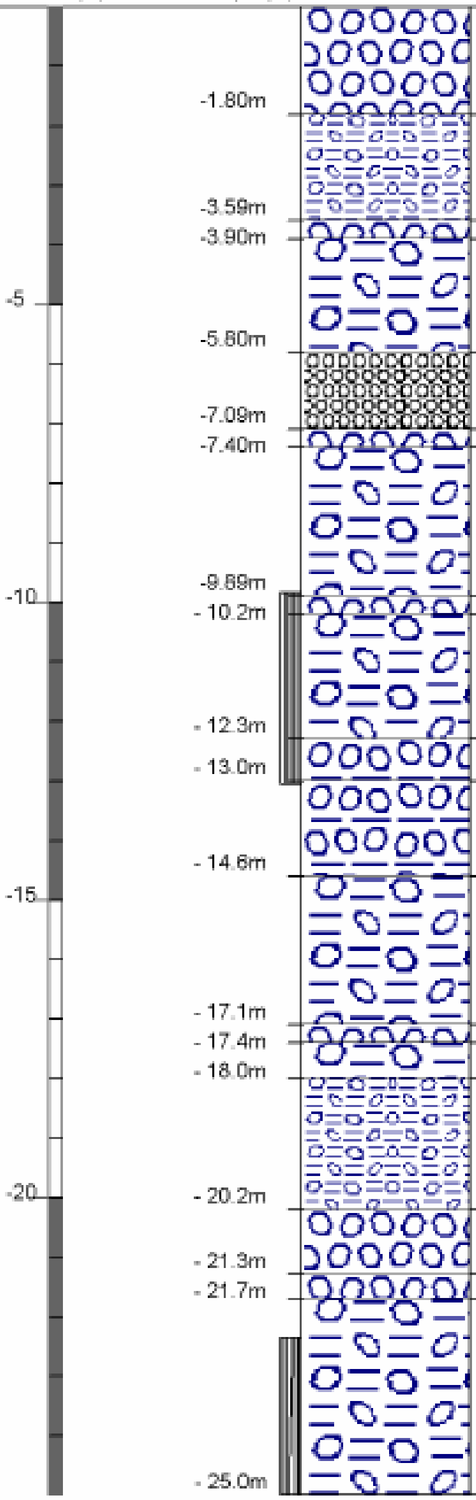
Gridref: H38:73173-58576 Accuracy : 3 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -42m Drill Date : 10/01/2008



Borelog for well I37/0006

Gridref: I37:0803-8591 Accuracy : 3 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary/Percussion
Drill Depth : -25m Drill Date : 18/05/1998

Environment Canterbury
Your regional council



Depth(m)	Full Drillers Description	Formation Code
	Large Cobbly Gravel	
-1.80m	Clay with less fine Gravel	
-3.59m	Boulders	
-3.90m	Cobbly Claybound Gravel	
-5.80m	Fine Gravel with rare cobbles	
-7.09m	Coarse Gravel	
-7.40m	Coarse Claybound Gravel	
-9.89m	Coarse Gravel	
- 10.2m	Coarse Claybound Gravel	
- 12.3m	Clay, less Gravel	
- 13.0m	Fine Gravel and Clay, wet	
- 14.6m	Coarse Claybound Gravel	
- 17.1m	Coarse Gravel	
- 17.4m	Coarse Gravel and Clay	
- 18.0m	Fine Gravel and Clay	
- 20.2m	Coarse Gravel	
- 21.3m	Coarse Gravel	
- 21.7m	Coarse Claybound Gravel	
- 25.0m		

Borelog for well I37/0007

Gridref: I37:0794-8595 Accuracy : 3 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary/Percussion
Drill Depth : -25m Drill Date : 14/05/1998

Depth(m)	Full Drillers Description	Formation Code
-1.20m	Coarse Gravel and Clay	
-6.09m	Clay Fine Gravel	
-6.50m	Coarse Gravel	
-8.39m	Fine Gravel and Clay	
-9.10m	Coarse Gravel (boulder)	
- 10.6m	Coarse Gravel	
- 10.9m	Coarse Gravel (boulder)	
- 12.3m	Coarse Gravel	
- 13.5m	Fine Gravel and Clay	
- 13.8m	Coarse Gravel (boulder)	
- 15.5m	Claybound Gravel	
- 18.1m	Coarse Gravel and Clay	
- 18.4m	Coarse Gravel (boulder)	
- 19.7m	Coarse Claybound Gravel	
- 22.3m	Coarse Claybound Gravel	
- 22.6m	Coarse Gravel (boulder)	
- 23.0m	Coarse Claybound Gravel	
- 25.0m	Cobbly Claybound Gravel	

Scale(m): -5, -10, -15, -20

Borelog for well I37/0007

Gridref: I37:0794-8595 Accuracy : 3 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Rotary/Percussion
Drill Depth : -25m Drill Date : 14/05/1998

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Depth(m)	Full Drillers Description	Formation Code
-1.20m	Coarse Gravel and Clay	
-6.09m	Clay Fine Gravel	
-6.50m	Coarse Gravel	
-8.39m	Fine Gravel and Clay	
-9.10m	Coarse Gravel (boulder)	
- 10.6m	Coarse Gravel	
- 10.9m	Coarse Gravel (boulder)	
- 12.3m	Coarse Gravel	
- 13.5m	Fine Gravel and Clay	
- 13.8m	Coarse Gravel (boulder)	
- 15.5m	Claybound Gravel	
- 18.1m	Coarse Gravel and Clay	
- 18.4m	Coarse Gravel (boulder)	
- 19.7m	Coarse Claybound Gravel	
- 22.3m	Coarse Claybound Gravel	
- 22.6m	Coarse Gravel (boulder)	
- 23.0m	Coarse Claybound Gravel	
- 25.0m	Cobbly Claybound Gravel	

Scale(m): -5, -10, -15, -20
Water Level

Borelog for well I37/0013

Gridref: I37:07233-87820 Accuracy : 2 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -22m Drill Date : 1/05/2000

Environment Canterbury
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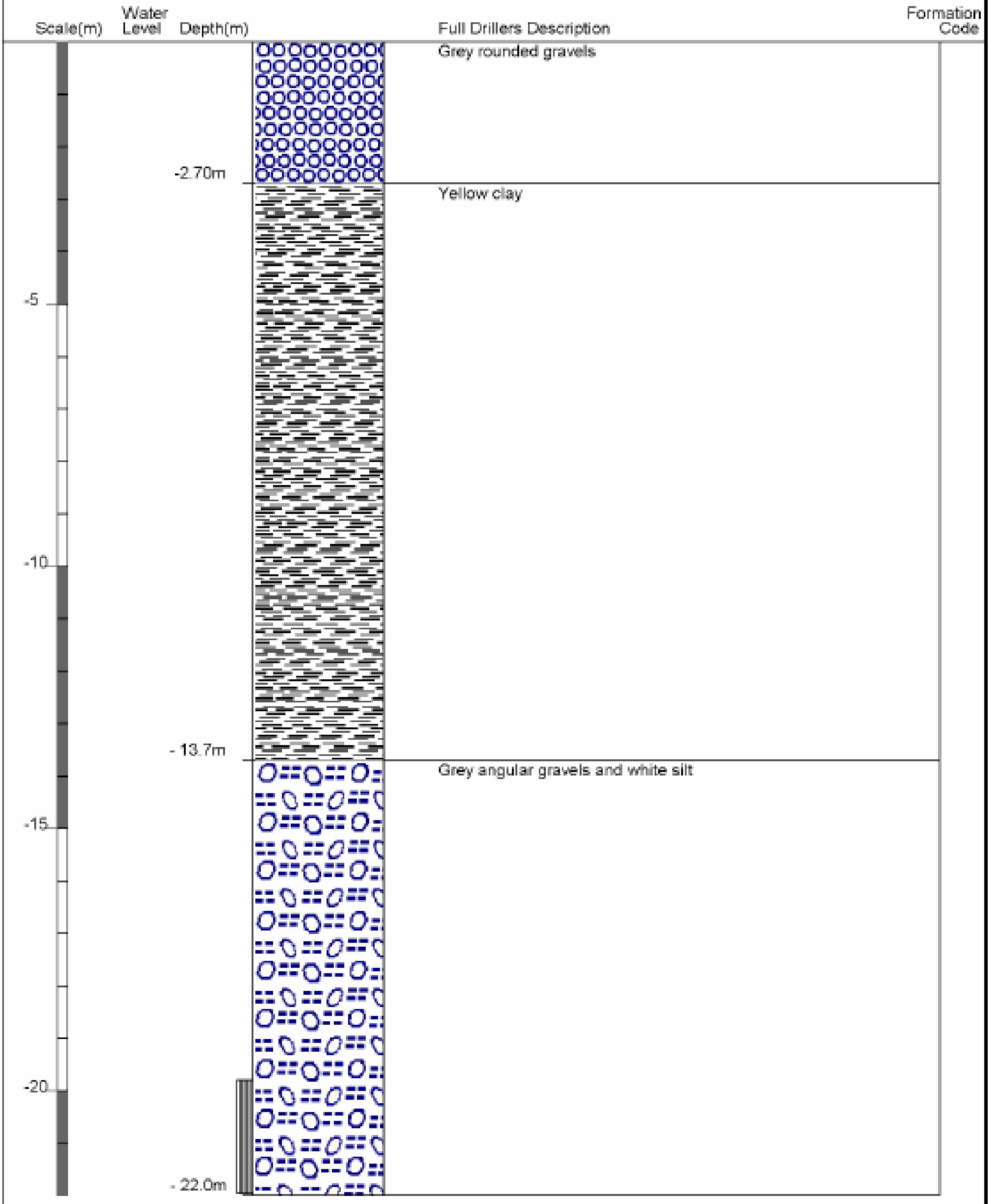
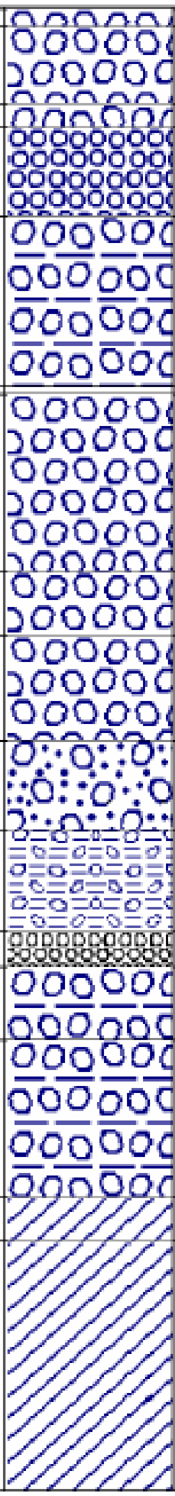


Borelog for well I37/0023

Gridref: I37:0117-8291 Accuracy : 5 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -184m Drill Date :

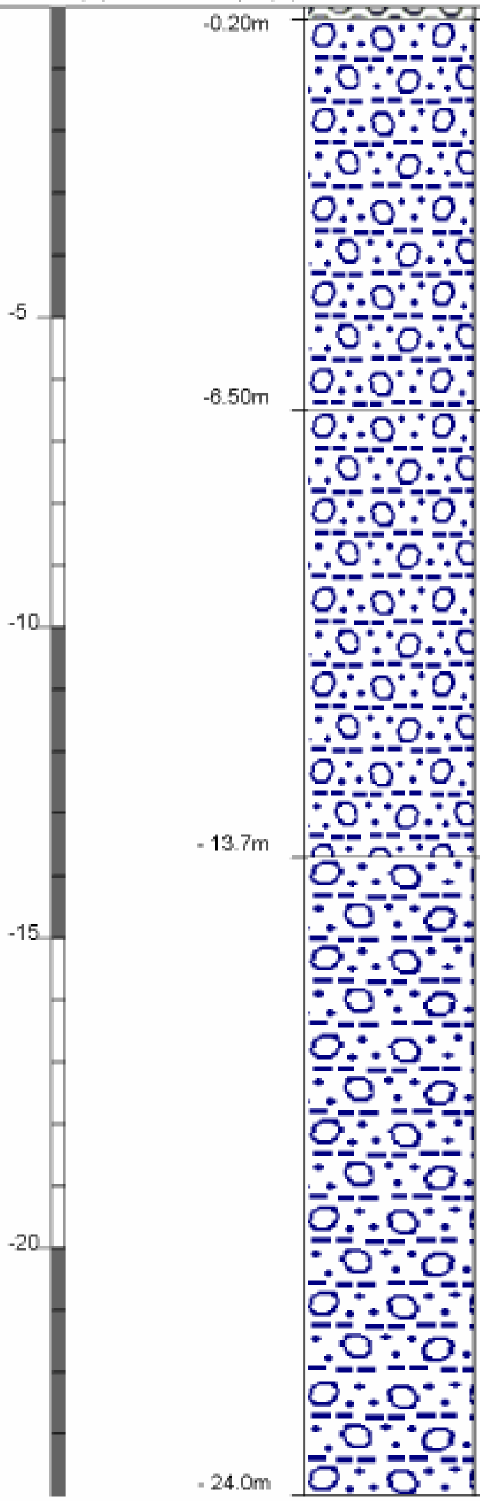
Scale(m): -10, -20, -30, -40, -50, -60, -70, -80, -90, -100, -110, -120, -130, -140, -150, -160, -170, -180



Water Level	Depth(m)	Full Drillers Description	Formation Code
	-0.30m	Topsoil	
	-2.50m	Grey gravels boulders	
	- 12.0m	Grey brown big loose gravels	
	- 15.0m	Yellow claybound brown grey gravels	
	- 26.0m	Brown grey gravels, dribble H2O	
	- 47.0m	Yellow brown claybound gravels, some boulders, dry	
	- 48.0m	Big rock	
	- 70.0m	Brown grey dry gravels/boulders-big	
	- 78.0m	Grey gravels, big rocks, hard to penetrate	
	- 91.0m	Grey rocks (big/hard) gravels	
	- 102.0m	Brown grey sandy gravels	
	- 114.5m	Brown grey clay small gravels - dry	
	- 119.0m	Grey small gravels, very small H2O	
	- 128.0m	Brown grey clay gravels - dry	
	- 147.5m	Brown grey claybound tight gravels - dry	
	- 153.0m	Dark grey-black schist/weathered rock, very slow penetration	
	- 184.0m	Dark grey unstable rock (broken rock) no H2O	

Borelog for well I38/0001

Gridref: I38:2119-7728 Accuracy : 4 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -24m Drill Date : 6/03/1995



Depth(m)	Full Drillers Description	Formation Code
-0.20m	Brown silty topsoil	
-6.50m	Brown to Yellow Brown silty fine to coarse sandy fine to very coarse gravel with minor to some clay. Gravel is subrounded to subangular strong to moderately weak mudstone. -compact	
- 13.7m	Green-Brown to Yellow silty fine to coarse sandy fine to coarse gravel with minor to some clay. Gravel is subrounded to subangular strong to moderately mudstone. -compact -sand is light Green to Yellow br	
- 24.0m	Grey to Yellow Brown silty fine to coarse sandy fine to very coarse (Occasional boulders) gravel with some clay. -thin Water-bearing seams. -Gravel is subrounded to subangular strong to moderately weak mudstone. -compact	

Borelog for well I38/0003

Gridref: I38:05769-57621 Accuracy : 2 (1=best, 4=worst)
Driller : Washingtons Exploration Ltd
Drill Method : Rotary Rig
Drill Depth : -48m Drill Date :

Water Level: -6.45 HWL; -6.45 LWL

Depth(m)	Full Drillers Description	Formation Code
-0.60m	Brown Silt	
-7.90m	Brown Silty Grey/Brown Gravel	
-9.10m	As Above -Dribble of Water	
-9.60m	Brown Schist Rock Boulder	
- 13.8m	Brown Silty Brown Gravel -pebbles, cobbles	
- 21.5m	Brown Silty Clay Brown Gravel -pebbles, cobbles -dribble of water	
- 22.9m	Brown Silty Claybound Gravel	
- 41.2m	Brown Schisty Rock	
- 48.0m	Blue Green Rock	

Scale(m): -5, -10, -15, -20, -25, -30, -35, -40, -45

Borelog for well I38/0012

Gridref: I38:93745-68545 Accuracy : 3 (1=best, 4=worst)
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -119m Drill Date : 11/07/2002

Environment Canterbury
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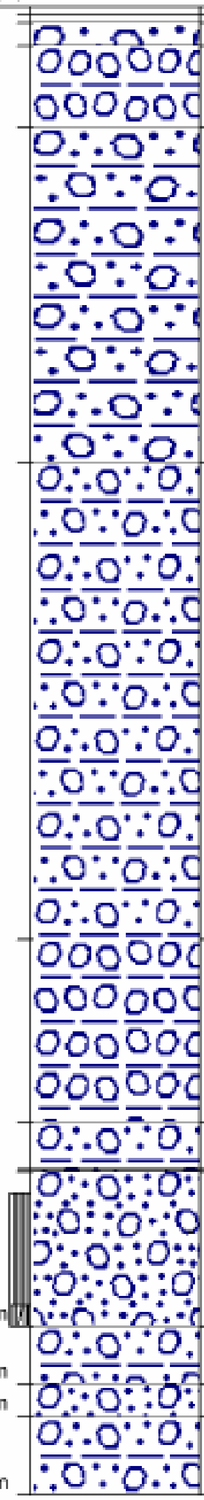


Depth(m)	Full Drillers Description	Formation Code
-0.60m	Earth	
-1.30m	Clay	
-3.10m	Large sandy claybound gravels	
-9.60m	Moderately sorted claybound gravels	
- 36.4m	Large sandy claybound gravels	
- 74.5m	Claybound sandy gravels	
- 89.1m	Claybound gravels	
- 92.9m	Sandy claybound gravels	
- 93.1m	Sandy gravels	
- 105.5m	Grey stained gravels little sand	
- 110.1m	Grey gravels some staining sand and bits of clay	
- 112.7m	Sandy grey gravels	
- 119.0m	Claybound sandy gravels	

Scale(m): -10, -20, -30, -40, -50, -60, -70, -80, -90, -100, -110

Water Level

Borelog for well I38/0014

Gridref: I38:9547-6515 Accuracy : 4 (1=best, 4=worst)
Driller : McNeill Drilling Co. Ltd
Drill Method : Tubex
Drill Depth : -24.5m Drill Date : 8/03/2005

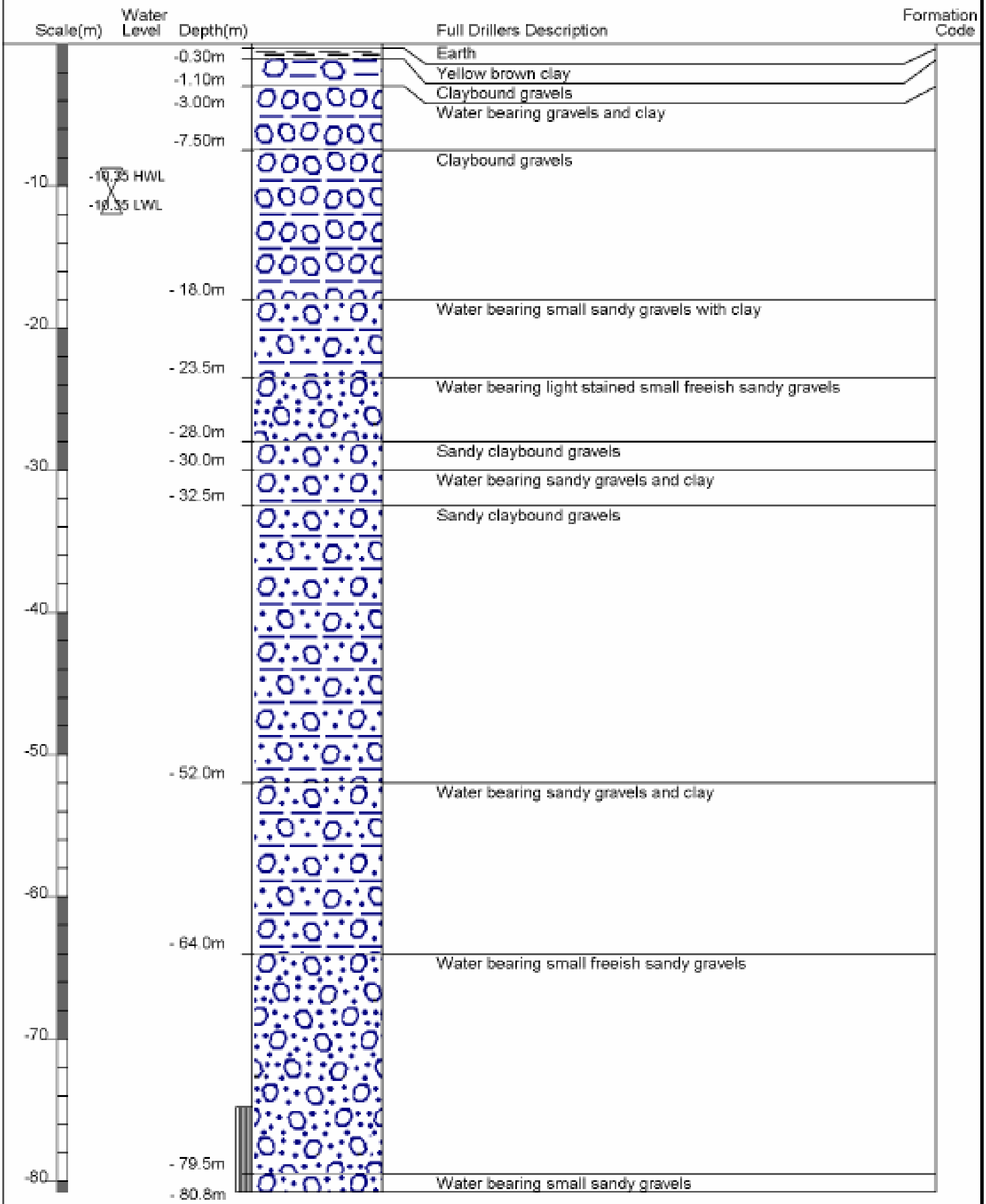
Depth(m)	Full Drillers Description	Formation Code
-1.80m	Silts, top soil	
-2.40m	Gravels silty	
-5.10m	Silts blue	
-9.80m	Silty gravels very silty	
- 12.5m	Sandy gravels	
- 14.3m	Sandy fijne gravels	
- 16.7m	Coarse gravels sandy	
- 19.5m	Sands	
- 24.0m	Coarse sandy gravels	
- 24.5m	Silty gravels	

Scale(m): -5, -10, -15, -20

Water Level

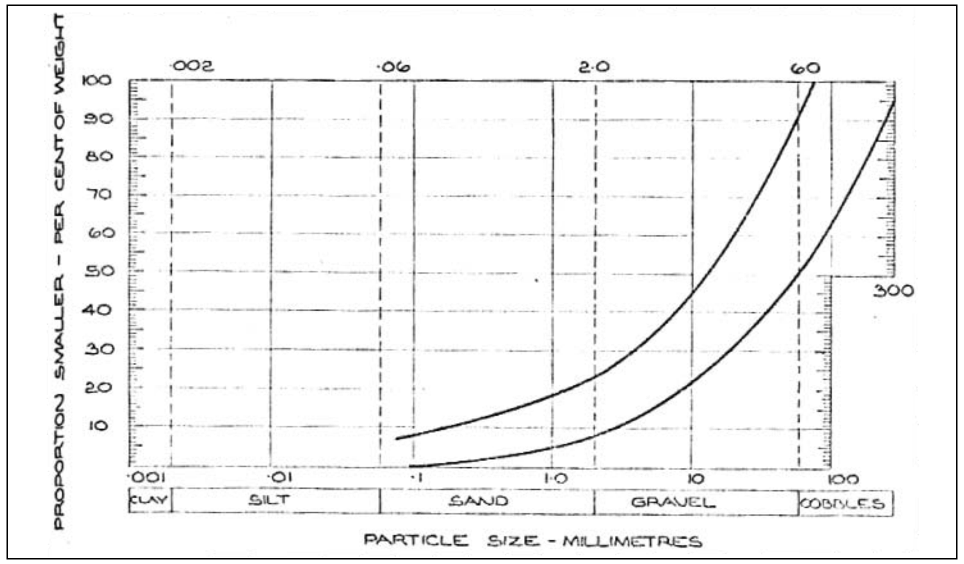
Borelog for well I38/0015

Gridref: I38:94292-66153 Accuracy : 2 (1=best, 4=worst)
Driller : McMillan Water Wells Ltd
Drill Method : 1st Rotary 2nd Cable
Drill Depth : -80.8m Drill Date : 4/02/2003

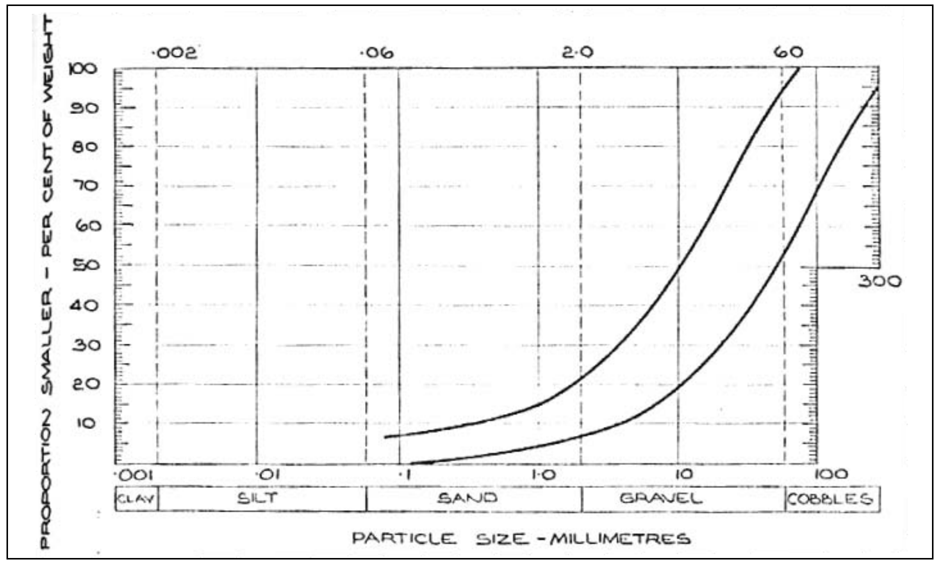


Appendix 7C

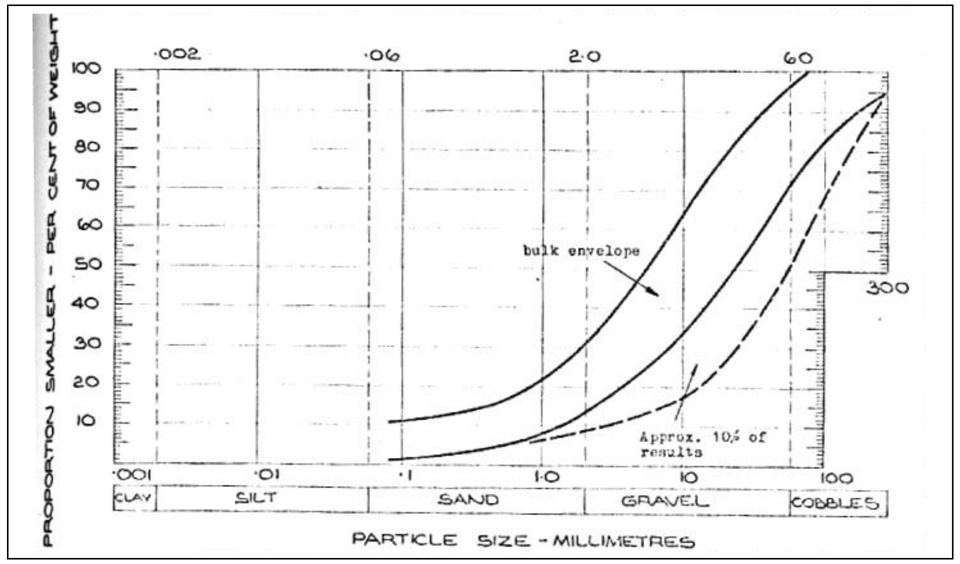
Grading Envelopes for Sieve Data



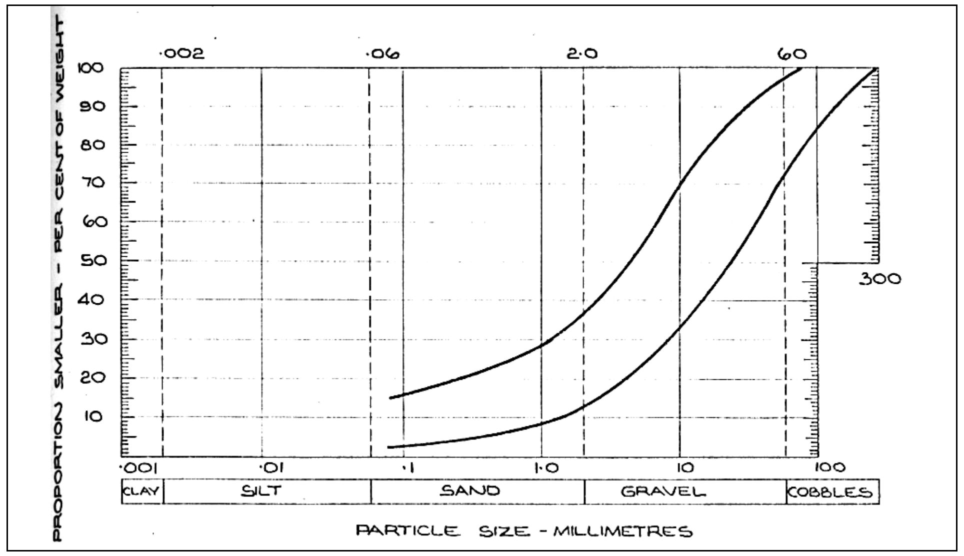
Alluvial Gravel



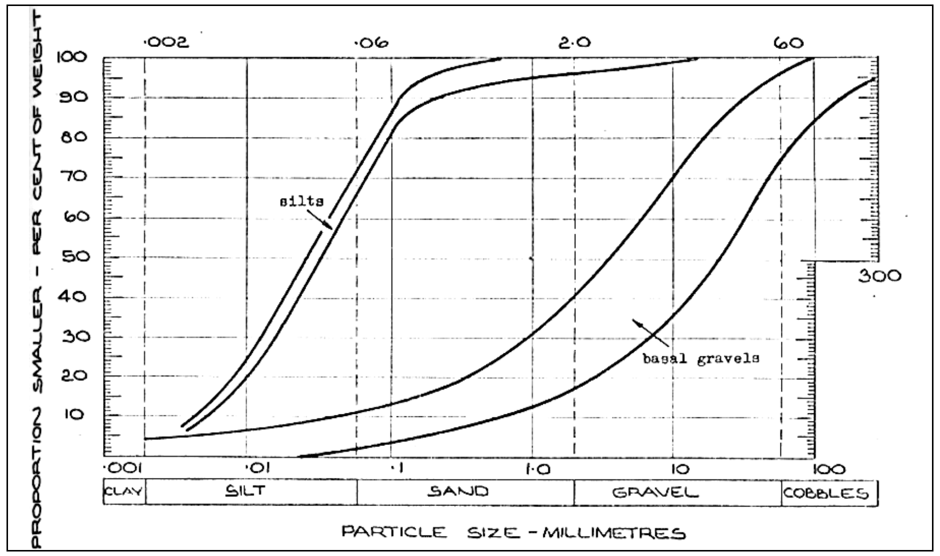
Tekapo Outwash Gravel



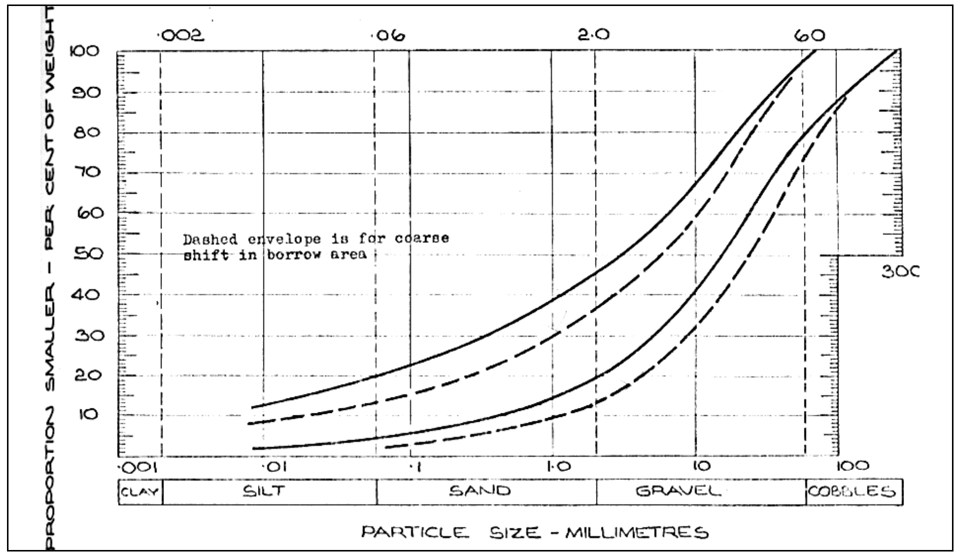
Mt John Outwash Gravel



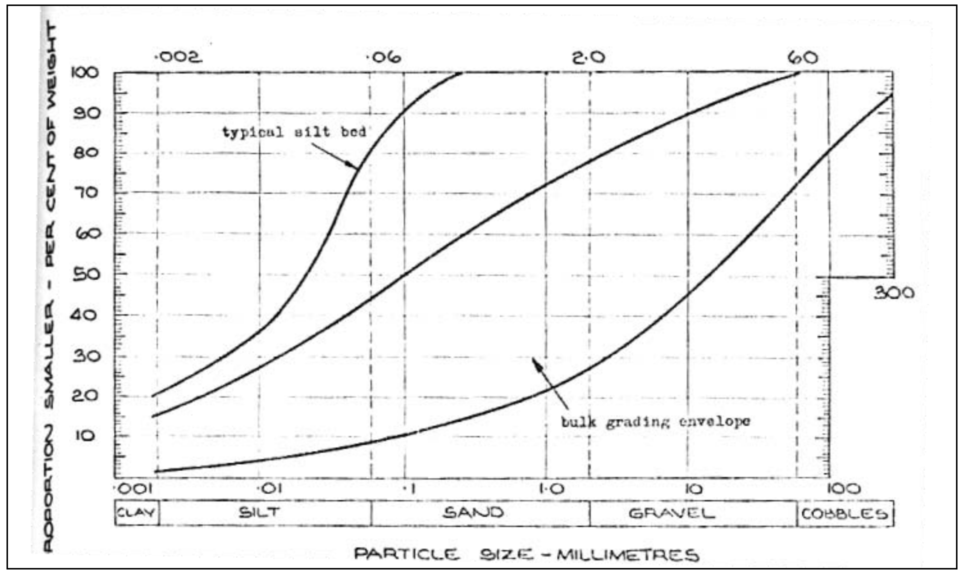
Balmoral Outwash Gravel



Interglacial Unit



Pre-Balmoral Outwash Gravel (Wolds)



Ostler Formation (Glentanner Formation)

Grading envelopes for sieve analyses conducted during investigations for the construction of the dams and canal system in the 1960's and 1970's within the Mackenzie Basin.

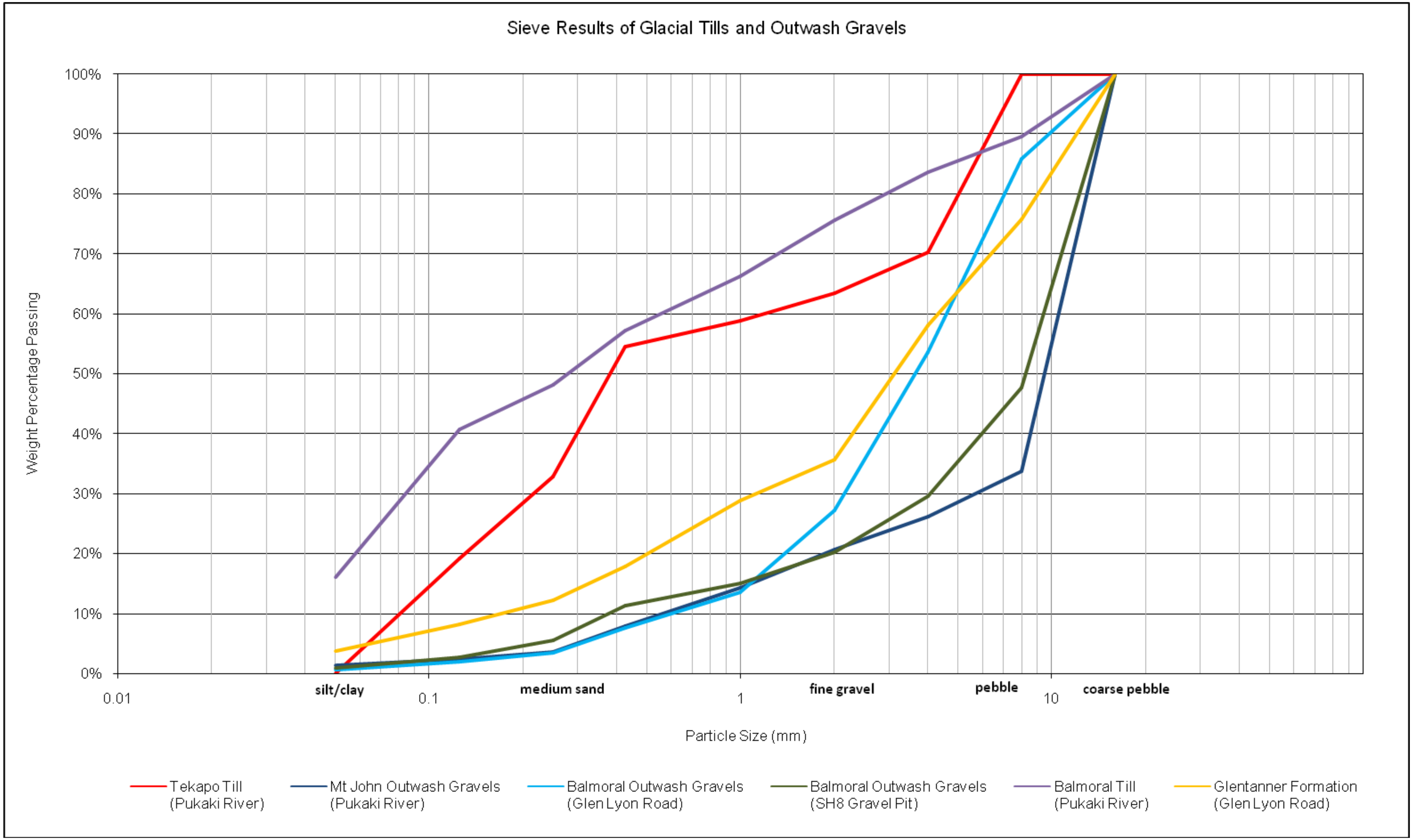


Figure 7.1: Results of sieve tests done on samples collected from various locations – the data is from the results of one sample only.

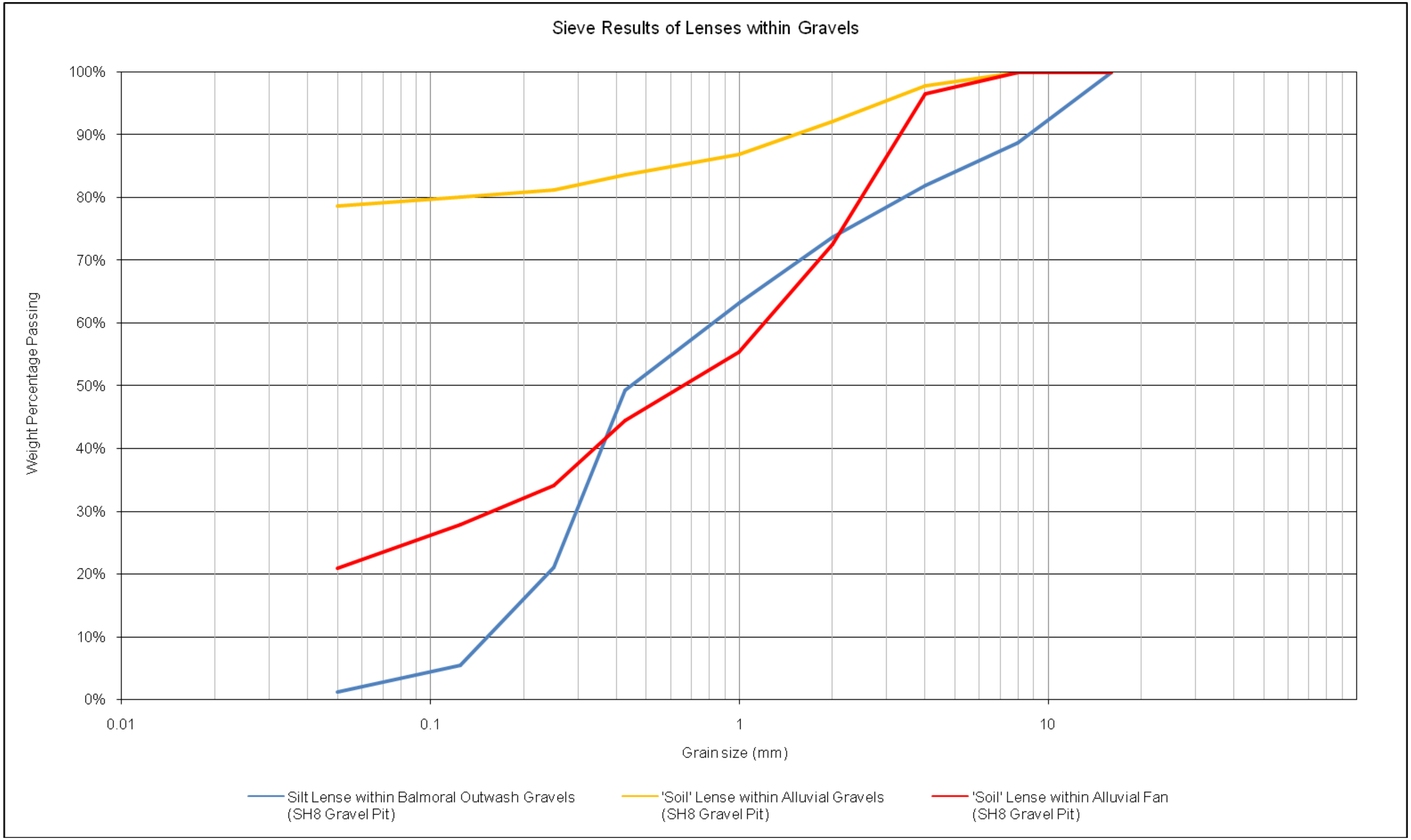


Figure 7.2: Results of sieve tests done on samples collected from silt/soil lenses within outwash and alluvial gravels – the data is from the results of one sample only.

Appendix 7D

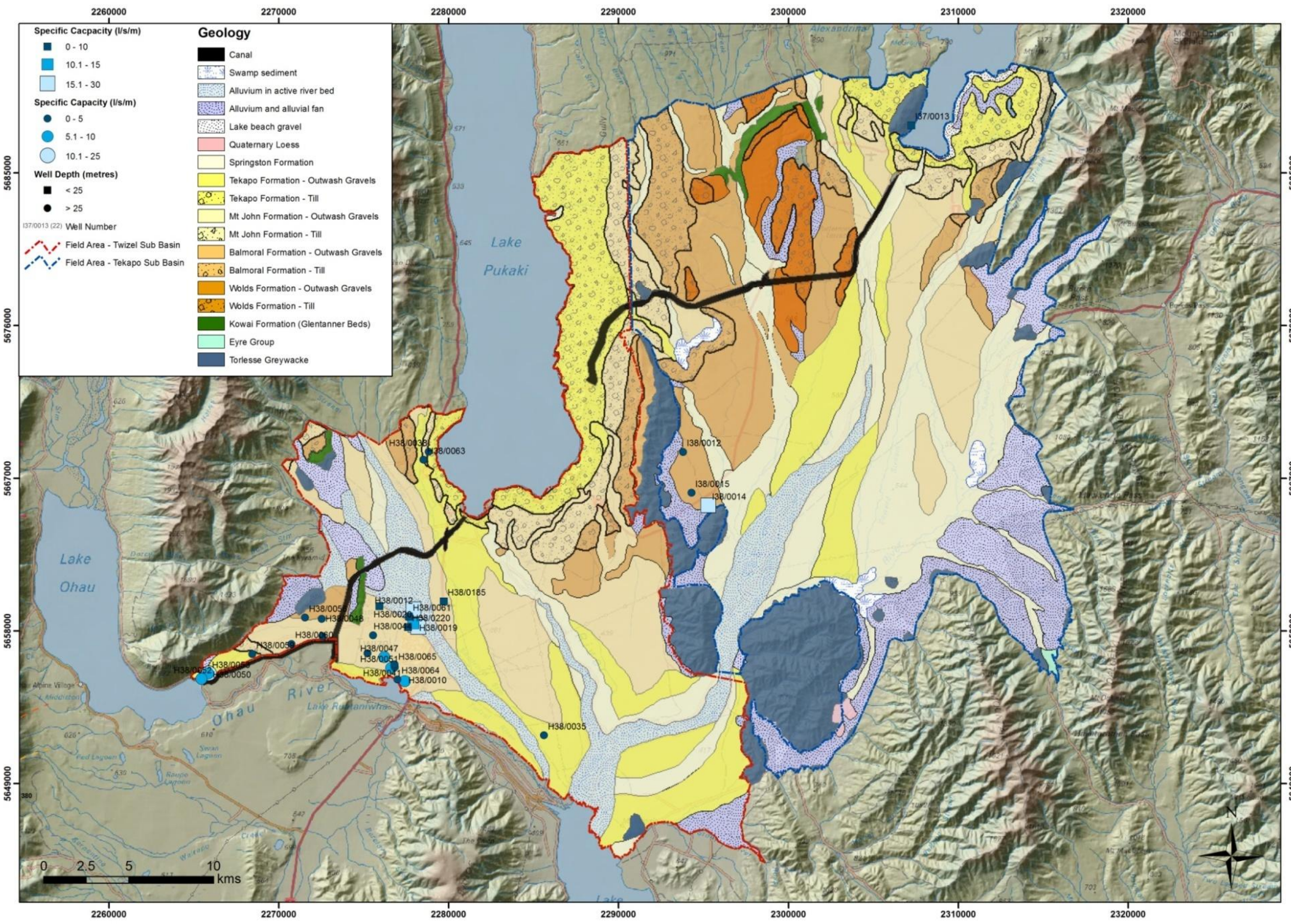
Specific Capacity and Transmissivity Data

(Maps with Respect to Surface Geology)

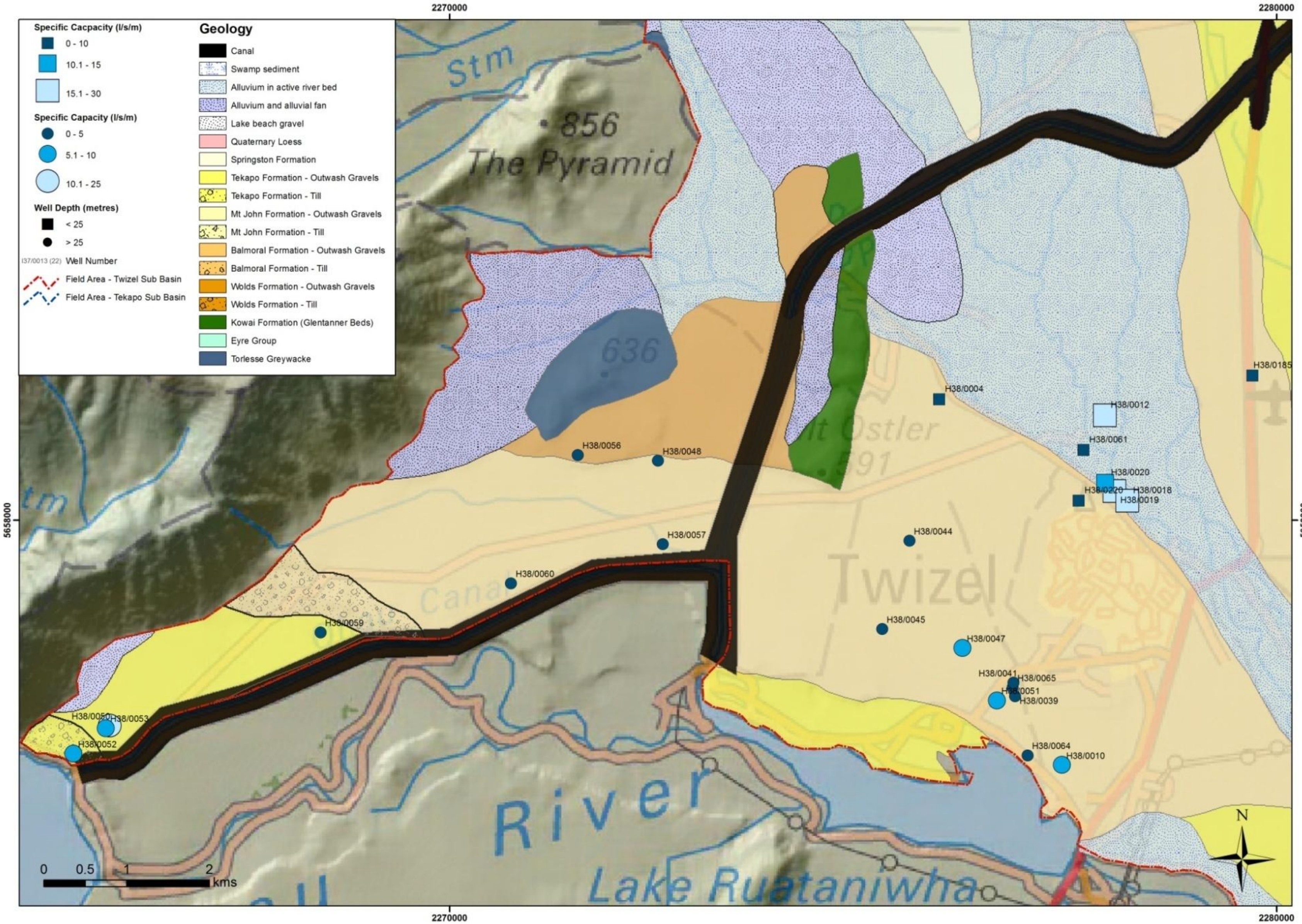
Calculations of Transmissivity Values from Yield and Drawdown Values

Well Number	Well Depth (m)	Yield (l/s)	Drawdown (m)	Specific Capacity (l/s/m)	Transmissivity* (m^2/day)
H38/0004	11	7	2	5	1381
H38/0010	31	12	2	6	1645
H38/0012	5	15	1	30	7711
H38/0018	17	84	2.1	25	6473
H38/0019	16	78	1.8	28	7216
H38/0020	16	76	3.6	14	3710
H38/0035	113	82	40	3	845
H38/0038	36	1	14	0.1	17
H38/0039	41	2	2	1	294
H38/0041	37	3	2	1	294
H38/0044	66	50	12	4	1114
H38/0045	71	50	11	5	1381
H38/0047	66	50	8	6	1645
H38/0048	51	2	2	1	294
H38/0050	41	2	0	22	5725
H38/0051	41	2	0	8	2168
H38/0052	53	2	0	6	1645
H38/0053	53	2	0	10	2686
H38/0056	95	1	8	0.2	48
H38/0057	66	3	2	2	573
H38/0059	53	2	3	1	294
H38/0060	83	1	5	0.2	75
H38/0061	17	2	5	0.4	119
H38/0063	48	2	24	0.1	23
H38/0064	39	2	4	0.3	105
H38/0065	41	2	1	2	573
H38/0185	23	2	0	7	1907
H38/0220	17	2	14	0.1	32
I37/0013	22	3	3	1	294
I38/0012	106	33	36	1	294
I38/0014	24	2	0	17	4470
I38/0015	81	8	45	0.2	51

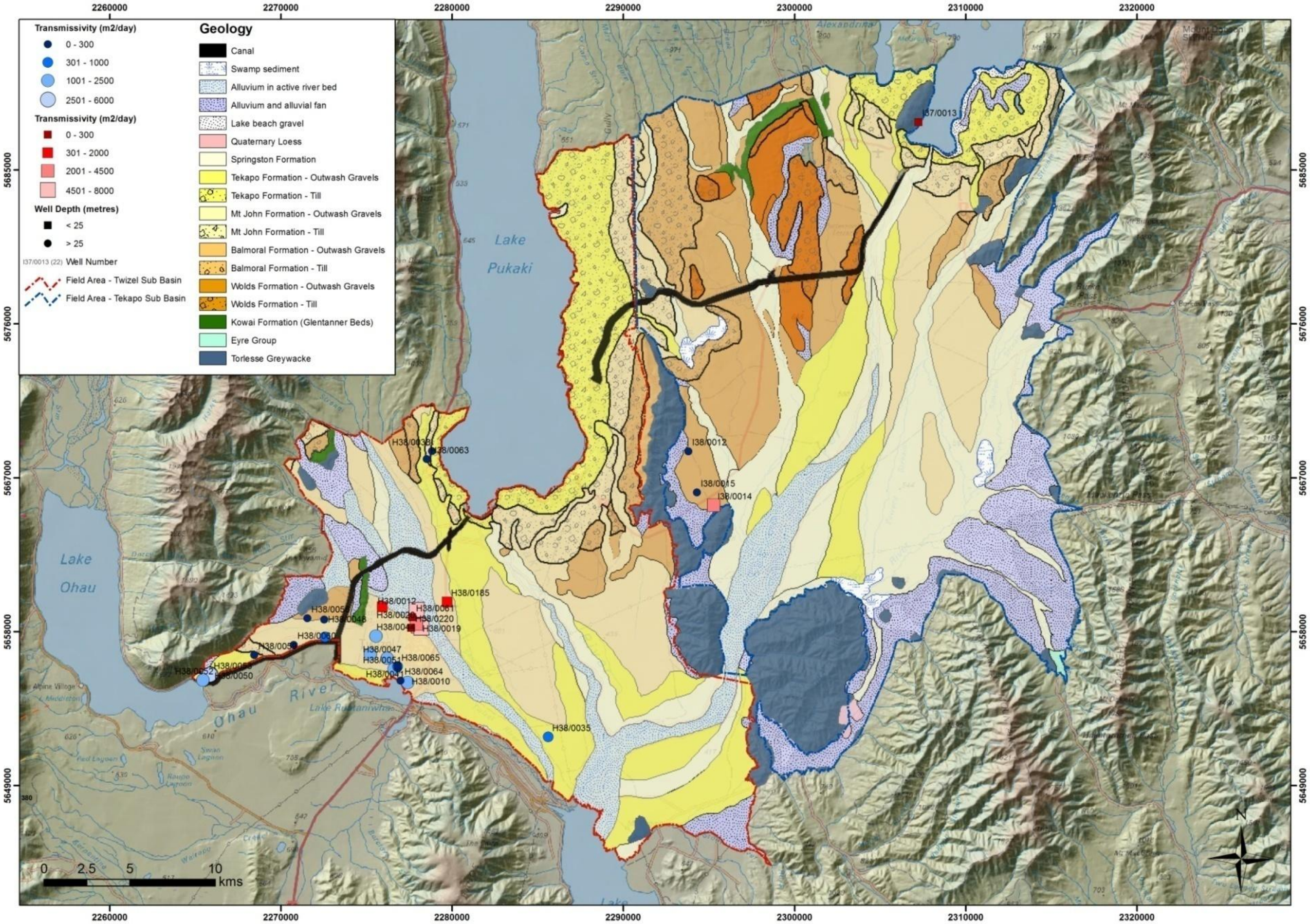
** Transmissivity Equation: T = 10^(0.96 x log(SC x 86.4) + 0.61) (Bal, 1996)*



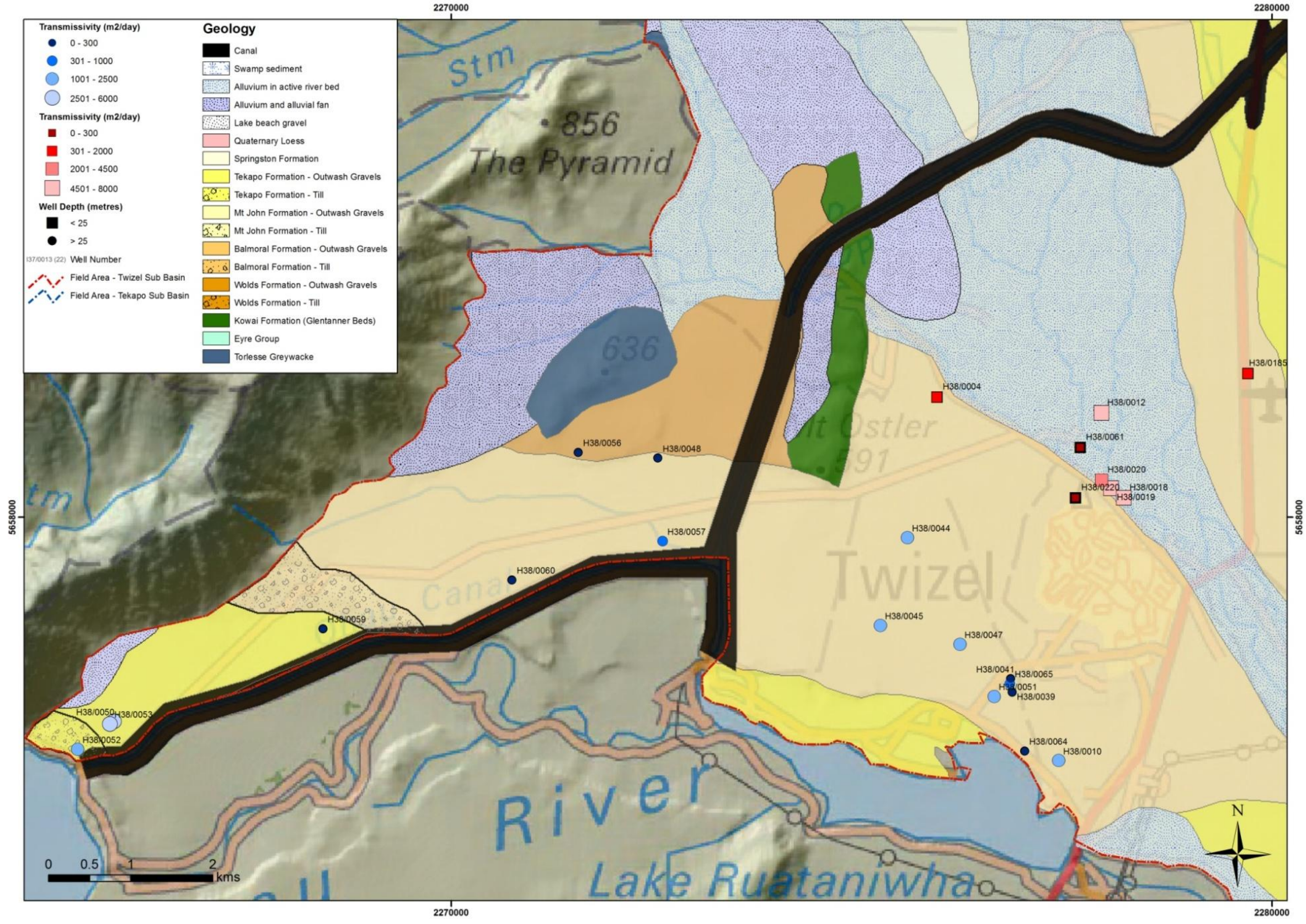
Specific capacity values in relation to surface geology for the Mackenzie Basin.



Specific capacity values in relation to surface geology for the Twizel area.



Transmissivity values in relation to surface geology for the Mackenzie Basin.



Transmissivity values in relation to surface geology for the Twizel area.

Appendix 7E

Piezometric Survey Data – February and September 2007

February Piezometric Survey

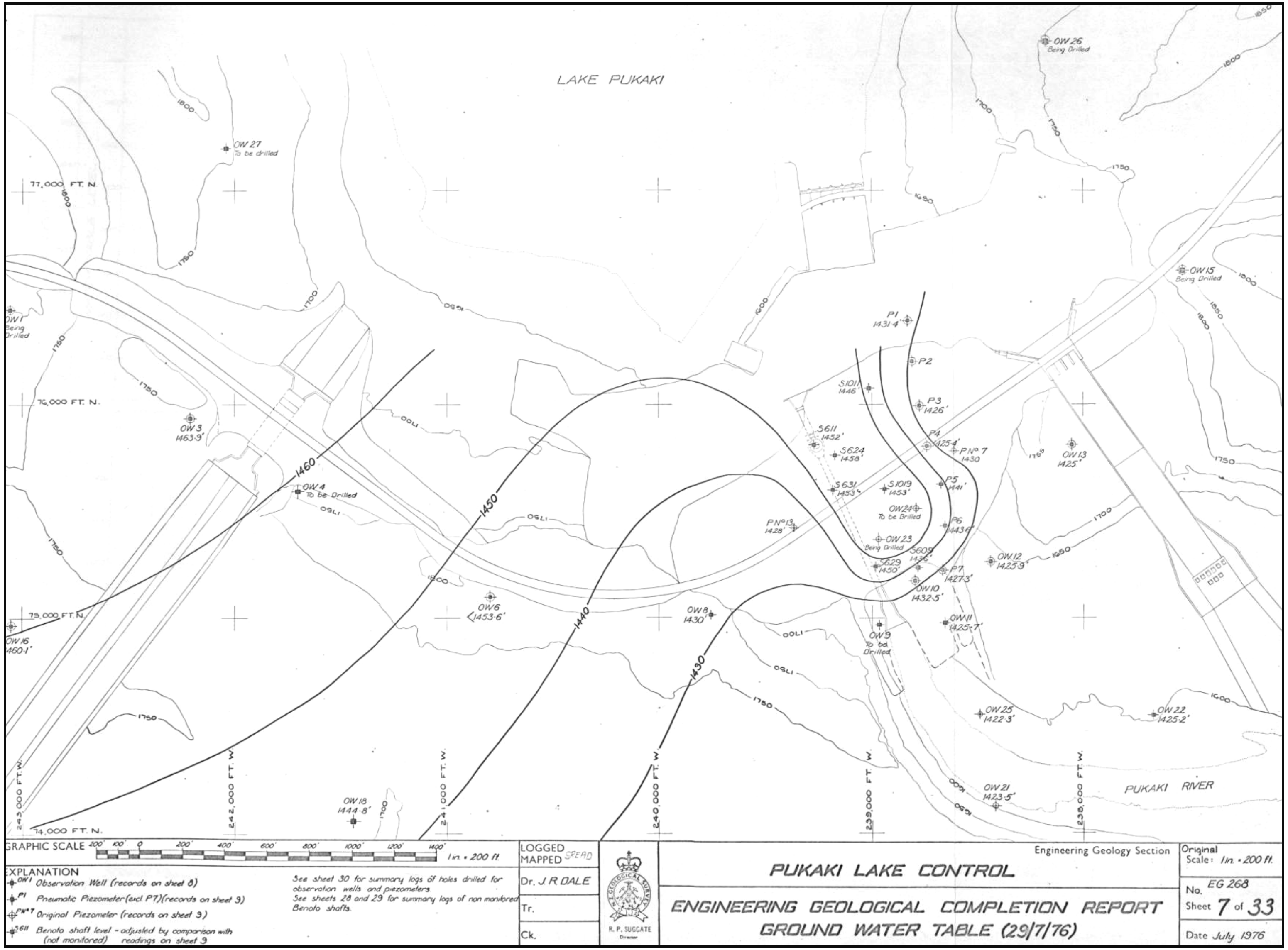
Well No.	Easting	Northing	Ground Surface Elevation (m)	Depth to Water (m)	Piezometric Surface Elevation (m)
H38/0004	2275921	5659464	484.66	-3.95	488.61
H38/0010	2277403	5655034	470.68	-22.20	448.48
H38/0012	2277924	5659271	471.08	-1.10	469.98
H38/0013	2275169	5658386	496.51	-19.70	476.81
H38/0016	2276730	5656096	476.33	-26.90	449.43
H38/0021	2279518	5658092	458.61	-1.90	456.71
H38/0025	2277547	5659071	470.25	-2.40	467.85
H38/0028	2277103	5658995	476.00	-2.50	473.50
H38/0029	2277671	5659023	471.00	-1.55	469.45
H38/0030	2279498	5657256	452.00	-2.80	449.20
H38/0032	2280387	5656095	446.00	-2.00	444.00
H38/0033	2280782	5655383	441.00	-1.70	439.30
H38/0038	2278823	5668570	589.00	-22.00	567.00
H38/0057	2272578	5657708	523.48	-44.20	479.28
H38/0061	2277666	5658849	474.59	-2.50	472.09
H38/0074	2272951	5660414	523.00	-8.40	514.60
H38/0100	2277558	5658886	479.99	-2.35	477.64
H38/0118	2279100	5658809	468.48	-2.40	466.08
H38/0119	2279197	5657318	455.44	-2.15	453.29
H38/0140	2279467	5657444	405.92	-3.70	402.22
I37/0029	2306189	5681599	699.52	-20.40	679.12
I37/0031	2307107	5680893	698.59	-35.20	663.39
I38/0012	2293791	5668555	562.00	-33.90	528.10
I38/0014	2295280	5665404	528.70	-3.90	524.80
I38/0015	2294292	5666153	530.00	-10.60	519.40
I38/0045	2302286	5669134	545.39	-4.05	541.34
I38/0049	2304560	5668897	560.27	-14.80	545.47
I38/0050	2305733	5668865	565.16	-13.50	551.66
I38/0052	2313265	5672144	595.00	-0.65	594.35
I38/0053	2301050	5650150	478.00	-1.30	476.70
New #2	2300011	5669377	551.05	-3.65	547.40
New #3	2301149	5669254	551.16	-5.50	545.66
OHAOW962	-	-	-	-	502.33
OHAOW963	-	-	-	-	501.78
PK10W18	-	-	-	-	450.39
PK10W21	-	-	-	-	442.10
RTHOW15	-	-	-	-	440.53
RTHOW19	-	-	-	-	440.36
TKAOP12	-	-	-	-	700.38
TKAOP24	-	-	-	-	678.11
TKAOP32	-	-	-	-	703.60
TKBO539	-	-	-	-	674.57

September Piezometric Survey

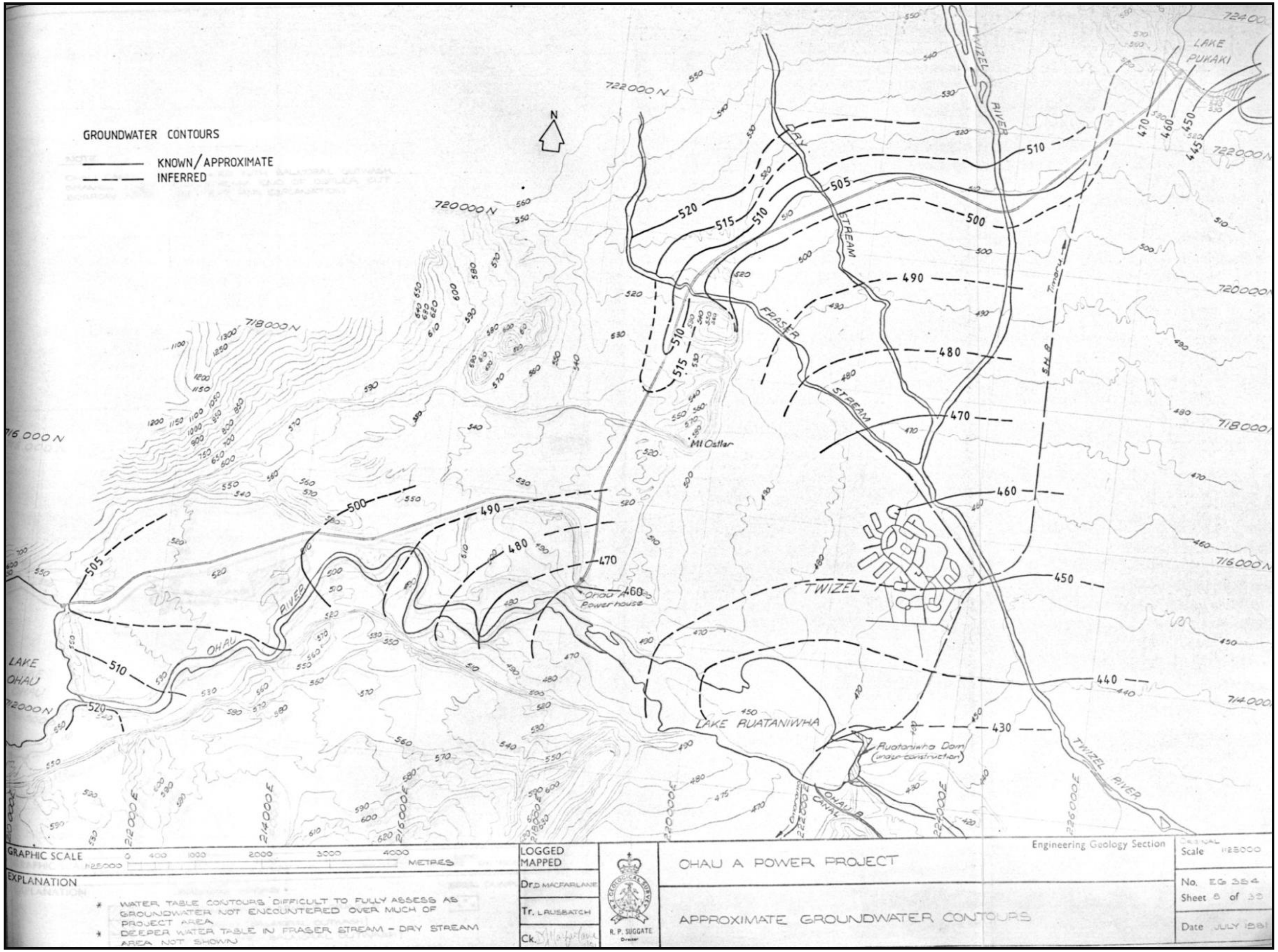
Well No.	Easting	Northing	Ground Surface Elevation (m)	Depth to Water (m)	Piezometric Surface Elevation (m)
H37/0007	2286994	5680425	530.50	0.50	531.00
H37/0009	2287155	5680469	545.00	2.00	547.00
H37/0010	2287174	5680239	544.00	1.00	545.00
H37/0011	2287223	5680071	543.80	1.20	545.00
H37/0013	2287371	5680140	560.00	1.00	561.00
H37/0014	2287416	5680371	561.50	1.50	563.00
H37/0016	2287520	5680246	575.20	0.80	576.00
H38/0004	2275921	5659464	484.66	-4.00	480.66
H38/0010	2277403	5655034	470.68	-22.50	448.18
H38/0012	2277924	5659271	471.08	-1.10	469.98
H38/0013	2275169	5658386	496.51	-19.60	476.91
H38/0016	2276730	5656096	476.33	-27.20	449.13
H38/0021	2279518	5658092	458.61	-2.20	456.41
H38/0022	2279518	5658184	459.26	-1.65	457.61
H38/0025	2277547	5659071	470.25	-2.35	467.90
H38/0030	2279498	5657256	452.00	-2.85	449.15
H38/0032	2280387	5656095	446.00	-2.00	444.00
H38/0033	2280782	5655383	441.00	-1.75	439.25
H38/0038	2278823	5668570	589.00	-24.25	564.75
H38/0044	2276591	5658363	492.10	-32.05	460.05
H38/0045	2275508	5657794	497.00	-39.70	457.30
H38/0047	2276072	5657080	487.08	-36.75	450.33
H38/0057	2272578	5657708	523.48	-46.00	477.48
H38/0058	2269149	5657290	559.00	-69.50	489.50
H38/0059	2268466	5656672	516.42	-10.45	505.97
H38/0063	2278510	5668102	580.48	-15.85	564.63
H38/0074	2272951	5660414	523.00	-8.65	514.35
H38/0118	2279100	5658809	468.48	-2.40	466.08
H38/0119	2279197	5657318	455.44	-2.10	453.34
H38/0140	2281963	5652245	405.92	-3.65	402.27
H38/0188	2268028	5656628	513.85	-6.85	507.00
I37/0013	2307233	5687820	741.00	0.95	741.95
I37/0029	2306189	5681599	699.52	-20.30	679.22
I37/0031	2307107	5680893	698.59	-35.25	663.34
I38/0003	2305769	5657621	533.00	-5.70	527.30
I38/0004	2303110	5651523	537.67	-0.95	536.72
I38/0012	2293791	5668555	562.00	-34.70	527.30
I38/0014	2295280	5665404	528.70	-5.00	523.70
I38/0015	2294292	5666153	530.00	-11.30	518.70
I38/0049	2304560	5668897	560.27	-15.95	544.32
I38/0050	2305733	5668865	565.16	-15.85	549.31
I38/0052	2313265	5672144	595.00	-0.65	594.35
I38/0053	2301050	5650150	478.00	-3.90	474.10
I39/0004	2291659	5647649	377.00	-5.95	371.05
I39/0005	2290619	5647279	380.00	-5.00	375.00
I39/0007	2291560	5646817	380.23	-1.55	378.68
New #2	2300011	5669377	551.05	-3.70	547.35

Appendix 7F

Groundwater Contour Maps from Historical Data



Groundwater contours from data collected during the Pukaki canal construction (Read, 1976).



Groundwater contours from data collected during the Ohau canal construction (Macfarlane, 1981).

Appendix 7G

Monthly Water Level Data and Associated Graphs

Water level data for all wells monitored during this study

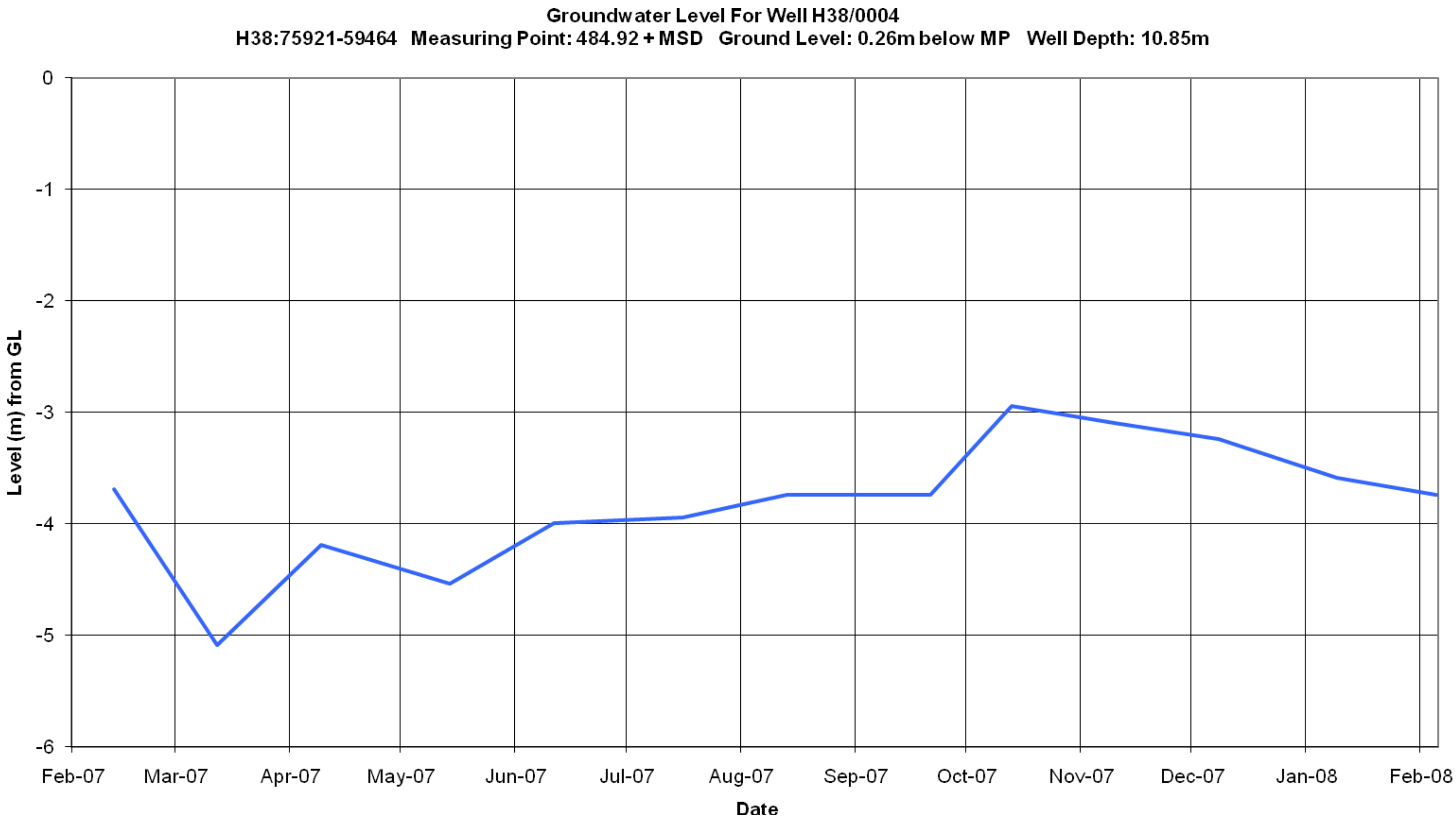
Well Number	Pump Installed ?	Well Depth (m)	Highest Water Level	Lowest Water Level	Feb-07	Mar-07	Apr-07	May-07	Jun-07	Jul-07	Aug-07	Sep-07	Oct-07	Nov-07	Dec-07	Jan-08	Feb-08
H38/0004	Y	11.10	-3.20	-5.35	-3.95	-5.35	-4.45	-4.80	-4.25	-4.20	-4.00	-4.00	-3.20	-3.35	-3.50	-3.85	-4.00
H38/0010	N	30.55	-22.15	-22.50	-22.20	-22.15	-22.20	-22.20	-22.30	-22.30	-22.45	-22.50	-22.45	-22.40	-22.40	-22.30	-22.30
H38/0012	Y	5.00	-1.05	-1.20	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10	-1.15	-1.10	-1.05	-1.10	-1.15	-1.20	-1.15
H38/0013	N	21.20	-19.20	-20.30	-19.70	-19.90	-20.15	-20.30	-20.05	-20.10	-20.00	-19.60	-19.20	-19.20	-19.35	-19.70	-19.90
H38/0016	N	30.00	-26.90	-27.20	-26.90	-26.90	-26.95	-27.00	-27.05	-27.10	-27.15	-27.20	-27.15	-27.05	-27.05	-27.00	-27.05
H38/0021	Y	12.20	-1.90	-2.60	-1.90	-2.00	-2.20	-2.60	-2.35	-2.20	-2.25	-2.20	-1.95	-1.95	-2.00	-2.05	-2.20
H38/0022	Y	4.90	-1.30	-1.80	-	-	-	-	-	-1.80	-1.80	-1.65	-1.35	-1.30	-1.40	-1.50	-1.70
H38/0025	Y	4.50	-2.20	-2.50	-2.40	-2.40	-2.50	-2.35	-2.35	-2.30	-2.40	-2.35	-2.20	-2.30	-2.40	-2.50	-2.40
H38/0028	Y	4.50	-	-	-2.50	-	-	-	-	-	-	-	-	-	-	-	-
H38/0029	Y	2.40	-	-	-1.55	-	-	-	-	-	-	-	-	-	-	-	-
H38/0030	Y	5.70	-2.55	-3.00	-2.80	-2.80	-3.00	-3.00	-2.90	-2.85	-2.95	-2.85	-2.55	-2.75	-2.80	-2.95	-2.90
H38/0032	N	2.85	-1.75	-2.15	-2.00	-2.00	-2.15	-2.10	-2.00	-1.90	-1.95	-2.00	-1.75	-1.90	-2.00	-2.10	-2.15
H38/0033	N	2.20	-1.60	-1.75	-1.70	-1.70	-1.70	-1.70	-1.65	-1.65	-1.65	-1.75	-1.65	-1.60	-1.75	-1.75	-1.75
H38/0038	Y	36.20	-22.00	-24.50	-22.00	-22.20	-22.50	-22.70	-22.90	-23.05	-23.10	-24.25	-22.80	-24.50	-22.45	-22.70	-23.00
H38/0044	Y	65.80	-22.90	-32.05	-	-	-	-	-	-32.05	-22.90	-32.05	-31.95	-31.95	-32.00	-32.00	-32.05
H38/0045	Y	71.30	-39.60	-39.70	-	-	-	-	-	-39.65	-39.60	-39.70	-39.60	-39.60	-39.60	-39.60	-39.65
H38/0047	Y	66.30	-32.70	-33.75	-	-	-	-	-	-33.75	-33.65	-36.75	-33.70	-33.65	-33.65	-32.70	-33.65
H38/0057	Y	66.00	-44.20	-46.00	-44.20	-44.45	-44.80	-45.20	-45.55	-45.90	-45.95	-46.00	-45.85	-45.05	-44.75	-44.90	-45.25
H38/0058	N	90.00	-67.05	-70.20	-	-	-	-	-	-70.20	-70.15	-69.50	-69.30	-67.85	-67.05	-67.95	-68.75
H38/0059	N	53.00	-10.05	-10.70	-	-	-	-	-	-10.70	-10.65	-10.45	-10.15	-10.05	-10.05	-10.30	-10.50
H38/0061	Y	17.00	-	-	-2.50	-	-	-	-	-	-	-	-	-	-	-	-
H38/0063	Y	48.00	-14.15	-23.20	-	-14.25	-19.15	-14.70	-14.70	-20.95	-15.25	-15.85	-14.15	-18.65	-21.40	-23.20	-14.85
H38/0074	N	12.60	-8.40	-8.70	-8.40	-8.45	-8.50	-8.60	-8.65	-8.70	-8.65	-8.65	-8.60	-8.60	-8.60	-8.60	-8.65
H38/0100	N	4.10	-	-	-2.35	-	-	-	-	-	-	-	-	-	-	-	-
H38/0118	N	2.90	-2.20	Dry	-2.40	-2.50	-2.70	Dry	Dry	-2.55	-2.50	-2.40	-2.20	-2.30	-2.35	-2.45	-2.55
H38/0119	N	2.85	-1.75	-2.30	-2.15	-2.20	-2.25	-2.30	-2.10	-2.10	-2.10	-2.10	-1.75	-2.00	-2.05	-2.20	-2.20

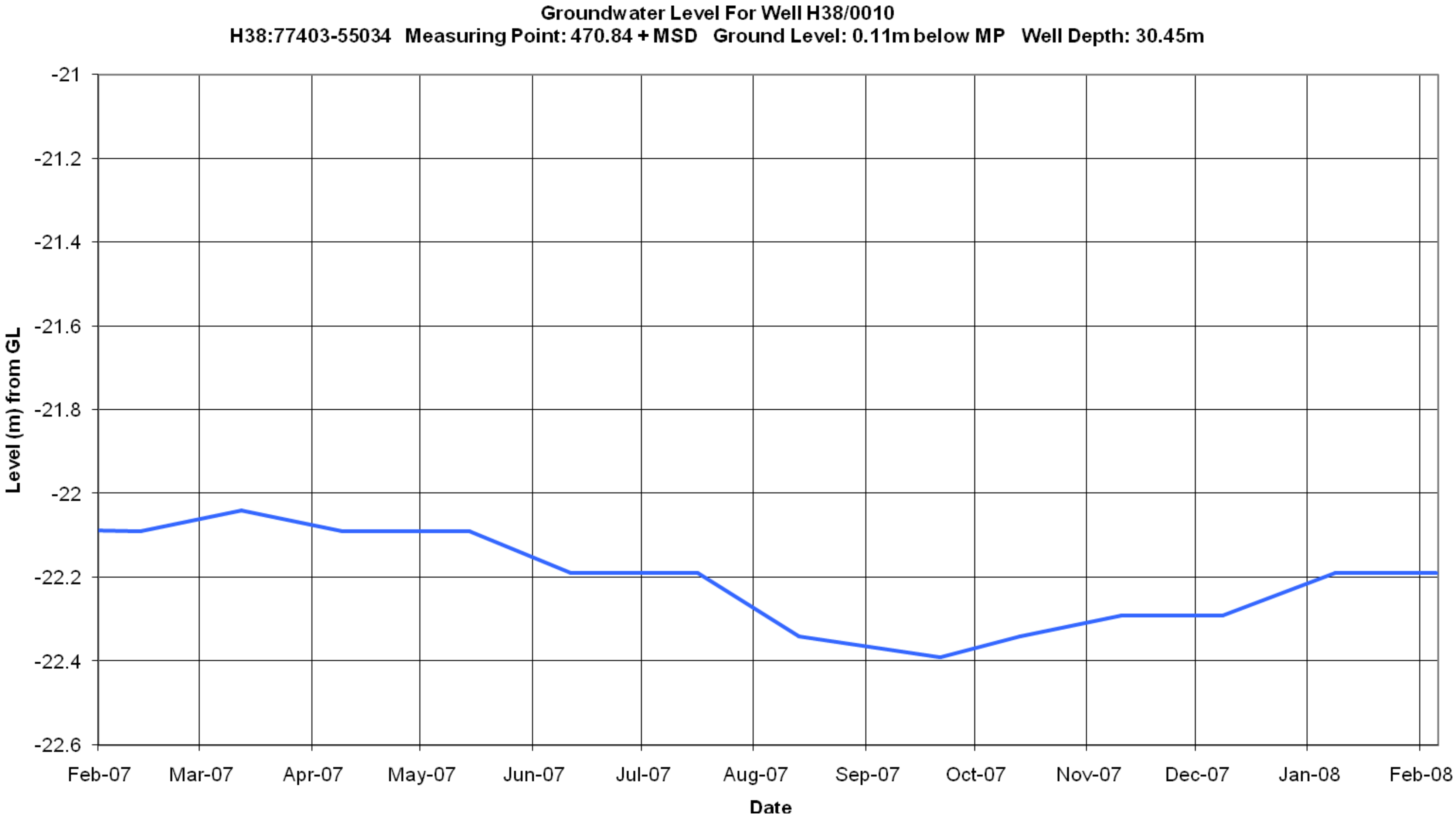
Well Number	Pump Installed ?	Well Depth (m)	Highest Water Level	Lowest Water Level	Feb-07	Mar-07	Apr-07	May-07	Jun-07	Jul-07	Aug-07	Sep-07	Oct-07	Nov-07	Dec-07	Jan-08	Feb-08
H38/0120	N	1.55	-1.55	Dry	Dry	Dry	-1.55	-1.50	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
H38/0140	N	7.45	-3.60	-3.85	-3.70	-3.70	-3.70	-3.65	-3.70	-3.65	-3.65	-3.65	-3.60	-3.80	-3.80	-3.80	-3.85
H38/0188	Y	36.00	-5.65	-7.20	-	-6.75	-6.80	-7.00	-7.20	-6.90	-6.85	-6.85	-6.05	-5.90	-6.25	-6.45	-5.65
I37/0013	Y	22.00	0.99	0.94	-	-	-	-	-	-	-	0.95	0.94	0.99	0.94	0.95	0.99
I37/0029	N	21.70	-20.25	-20.45	-20.40	-20.40	-20.40	-20.40	-20.40	-20.25	-20.30	-20.30	-20.35	-20.40	-20.45	-20.40	-20.40
I37/0031	N	35.40	-35.10	-35.30	-35.20	-35.20	-35.20	-35.10	-35.20	-35.20	-35.25	-35.25	-35.30	-35.25	-35.25	-35.25	-35.30
I37/0032	N	34.60	-33.65	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	-33.65	Dry	Dry	Dry
I38/0003	N	48.00	-5.70	-8.10	-	-7.50	-8.10	-8.00	-6.95	-6.50	-6.30	-5.70	-5.70	-6.20	-6.30	-6.50	-7.85
I38/0004	N	28.00	-0.60	-1.40	-	-1.20	-1.40	-1.20	-1.30	-1.25	-1.15	-0.95	-0.60	-0.75	-1.10	-1.25	-1.40
I38/0011	Y	6.00	-	-	-3.10	-	-	-	-	-	-	-	-	-	-	-	-
I38/0012	N	119.00	-33.80	-34.90	-33.90	-33.80	-34.00	-34.20	-34.45	-34.50	-34.65	-34.70	-	-35.65	-34.60	-34.65	-34.90
I38/0014	Y	23.95	-3.84	-5.35	-3.90	-3.84	-3.95	-4.00	-4.30	-4.55	-4.75	-5.00	-5.05	-5.20	-5.20	-5.30	-5.35
I38/0015	N	80.80	-10.35	-11.65	-10.60	-10.35	-10.50	-10.50	-10.80	-11.00	-11.15	-11.30	-	-11.45	-11.40	-11.50	-11.65
I38/0045	N	6.35	-4.00	Dry	-4.05	-4.05	-4.00	-4.00	-4.10	-4.05	-4.11	Dry	-	-4.10	-4.20	-4.20	Dry
I38/0049	N	17.40	-14.80	-15.95	-14.80	-14.90	-15.00	-15.20	-15.30	-15.60	-15.70	-15.95	-15.90	-15.80	-15.85	-15.85	-15.95
I38/0050	N	24.20	-13.50	-16.45	-13.50	-14.22	-14.75	-15.30	-15.80	-14.60	-15.00	-15.85	-14.80	-15.30	-15.75	-16.00	-16.45
I38/0052	Y	2.00	-0.55	-1.70	-0.65	-0.95	-1.20	-1.40	-1.40	-1.30	-1.10	-0.65	-0.60	-0.55	-0.70	-1.15	-1.70
I38/0053	Y	8.90	-1.30	-4.95	-1.30	-1.70	-1.70	-4.15	-4.25	-3.80	-3.80	-3.90	-3.95	-4.55	-1.40	-1.65	-4.95
I39/0004	N	69.61	-4.95	-6.00	-	-	-	-	-	-4.95	-5.95	-5.95	-5.95	-5.90	-5.95	-6.00	-5.05
I39/0005	N	50.00	-4.80	-5.20	-	-4.80	-4.85	-4.85	-4.95	-4.90	-4.95	-5.00	-5.00	-5.10	-5.15	-5.20	-5.10
I39/0007	Y	18.00	-1.25	-3.25	-	-1.50	-1.80	-2.00	-2.85	-1.85	-1.60	-1.55	-1.25	-1.35	-1.55	-1.85	-3.25
New #2	N	4.10	-3.28	-3.70	-3.65	-3.65	-3.65	-3.50	-3.60	-3.50	-3.70	-3.70	-	-3.28	-3.60	-3.70	-3.70
New #3	N	5.50	-5.00	Dry	-5.50	-5.05	-5.05	-5.00	Dry	-5.05	Dry	Dry	-	-5.10	Dry	-5.05	-5.05

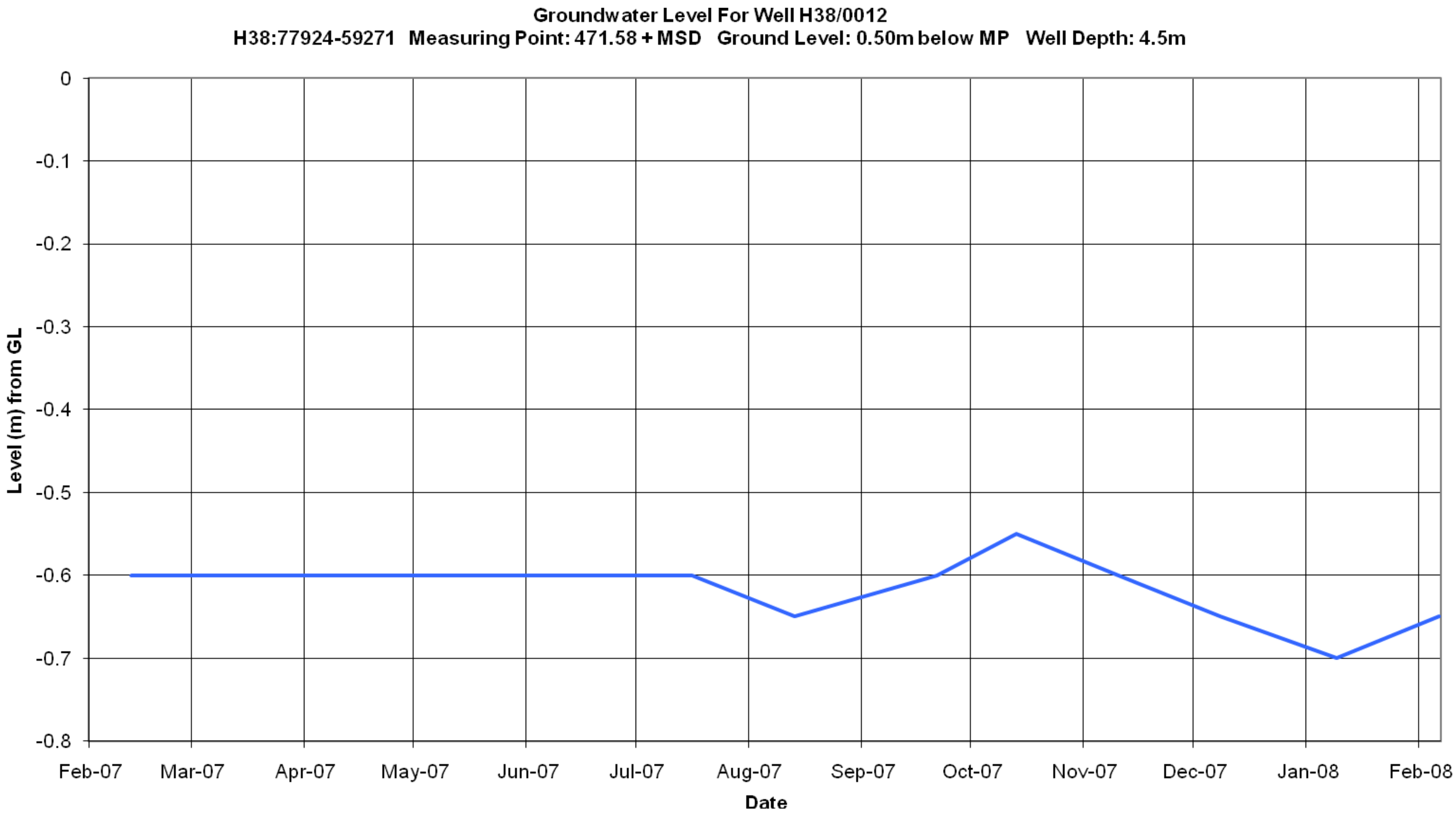
= suspect reading

= possible effect of pumping

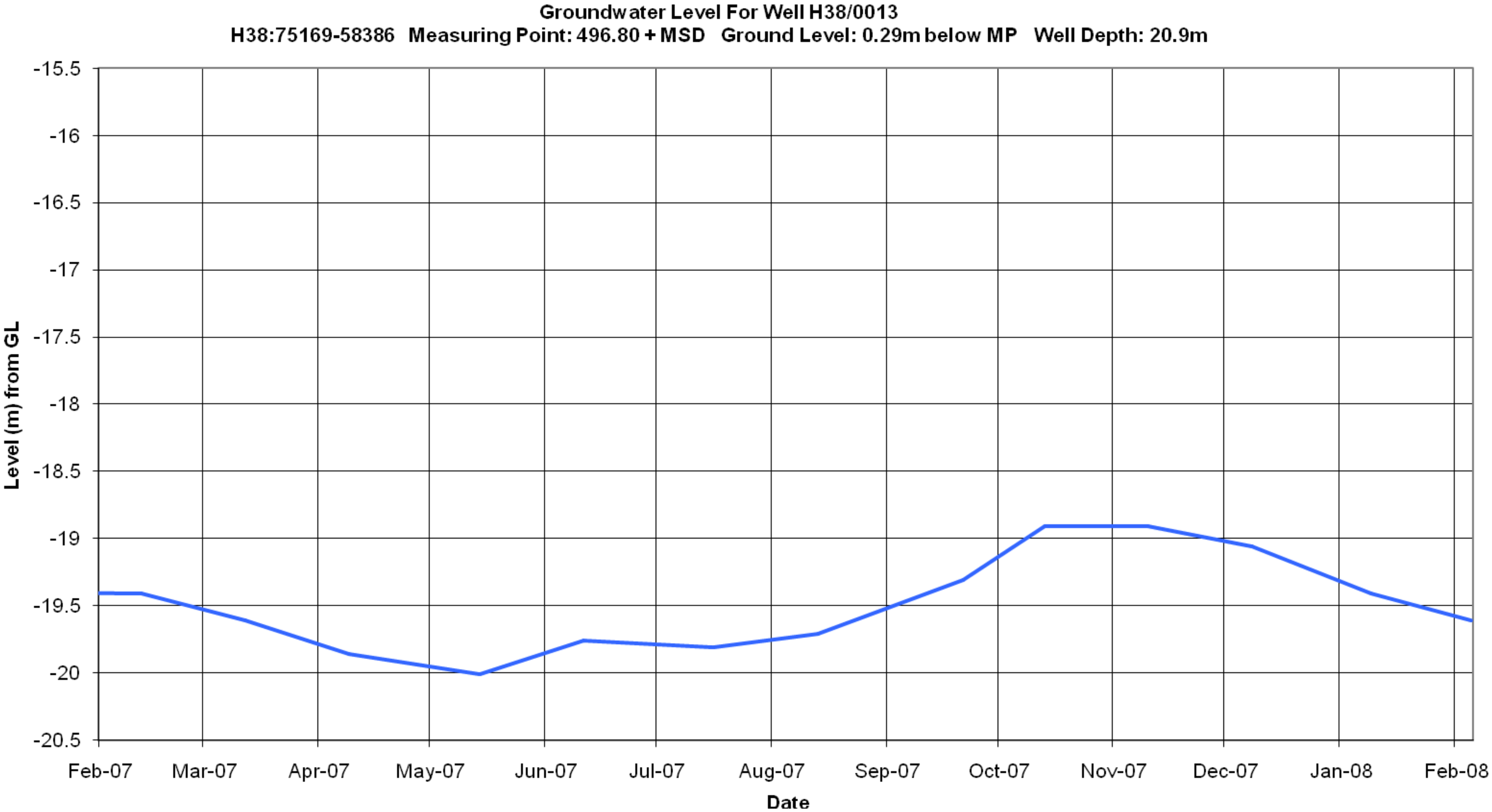
\- *= not measured*

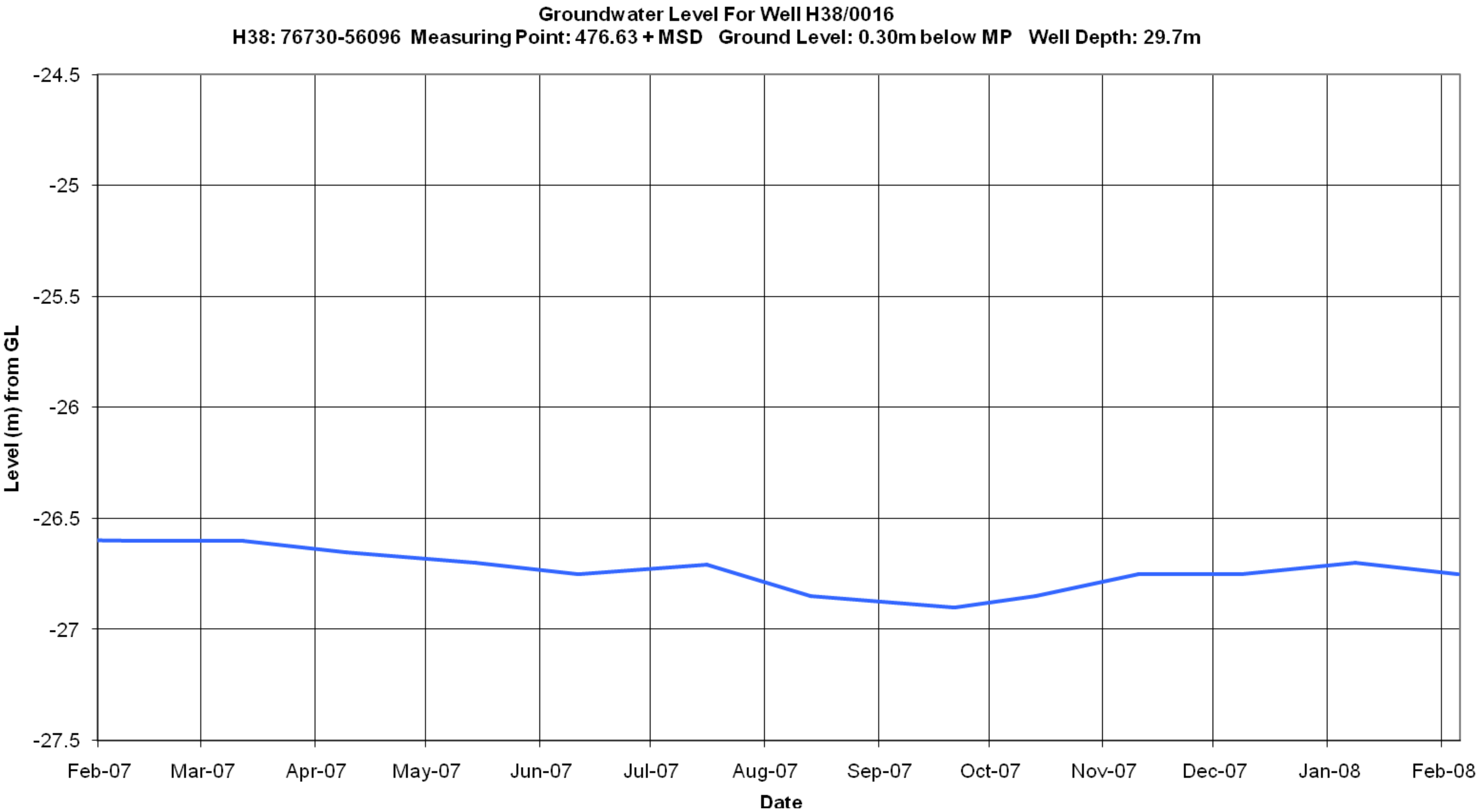

Groundwater Level For Well H38/0004
H38:75921-59464 Measuring Point: 484.92 + MSD Ground Level: 0.26m below MP Well Depth: 10.85m
Level (m) from GL
0
-1
-2
-3
-4
-5
-6
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

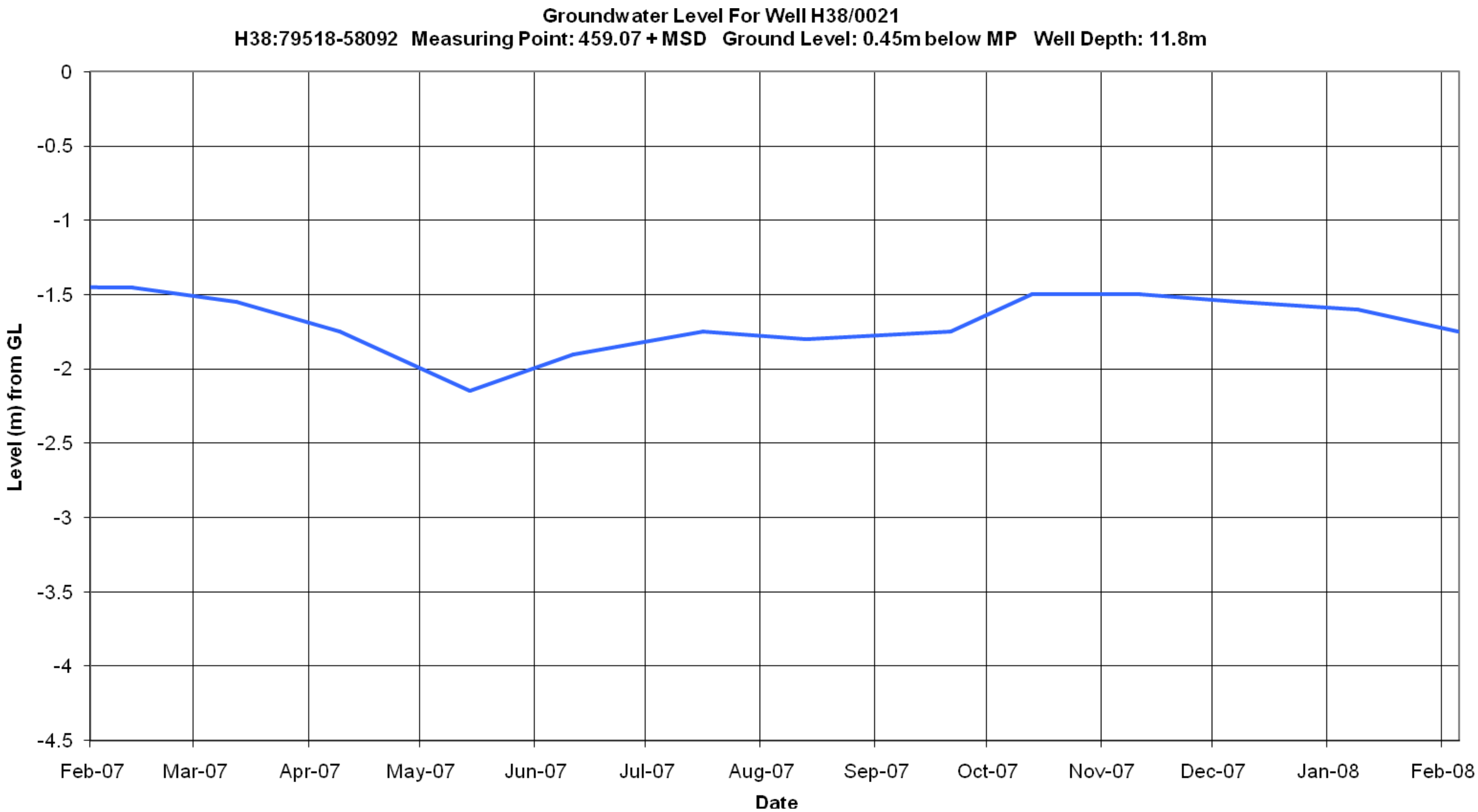

Groundwater Level For Well H38/0010
H38:77403-55034 Measuring Point: 470.84 + MSD Ground Level: 0.11m below MP Well Depth: 30.45m
Level (m) from GL
-21
-21.2
-21.4
-21.6
-21.8
-22
-22.2
-22.4
-22.6
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

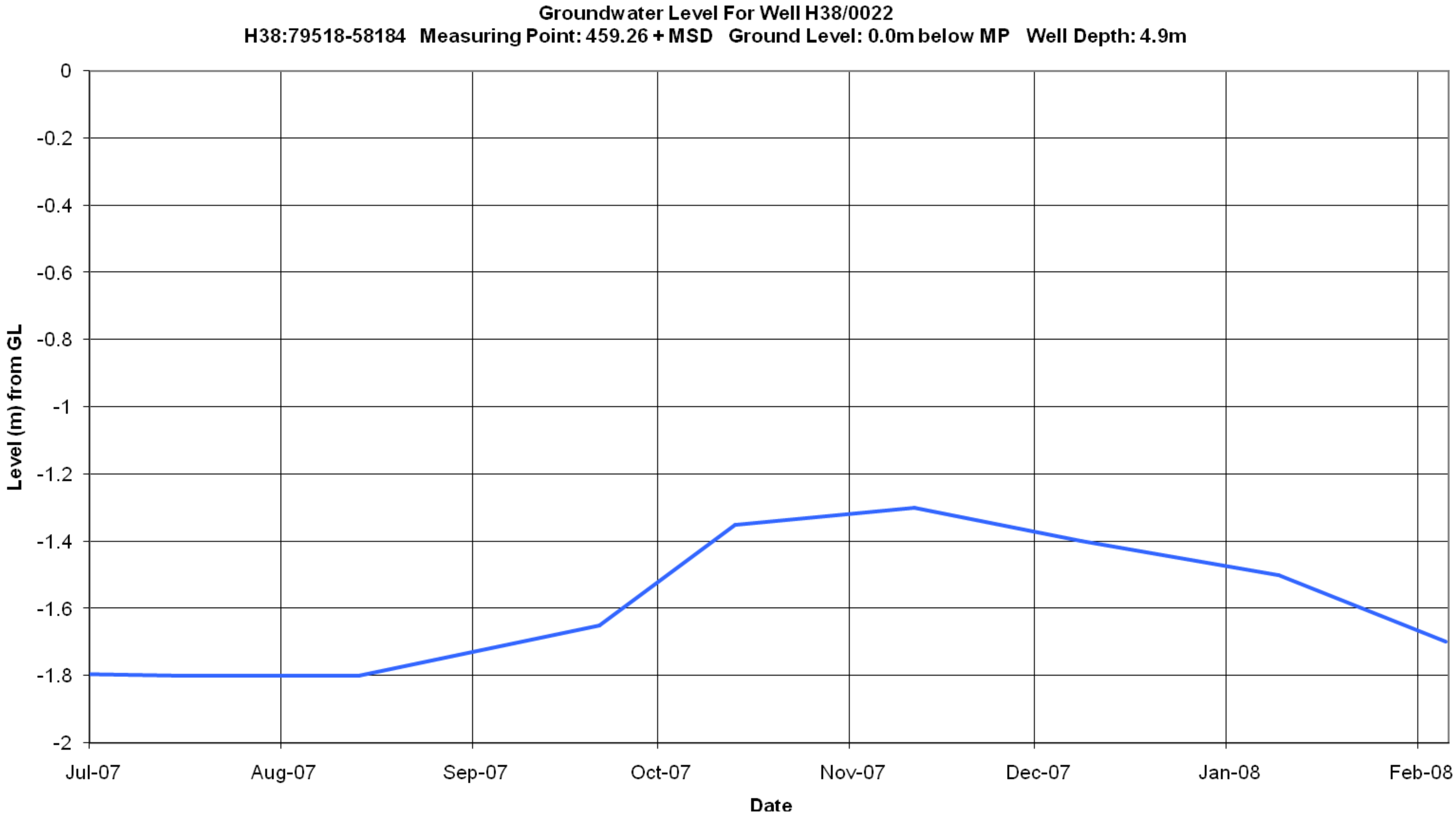


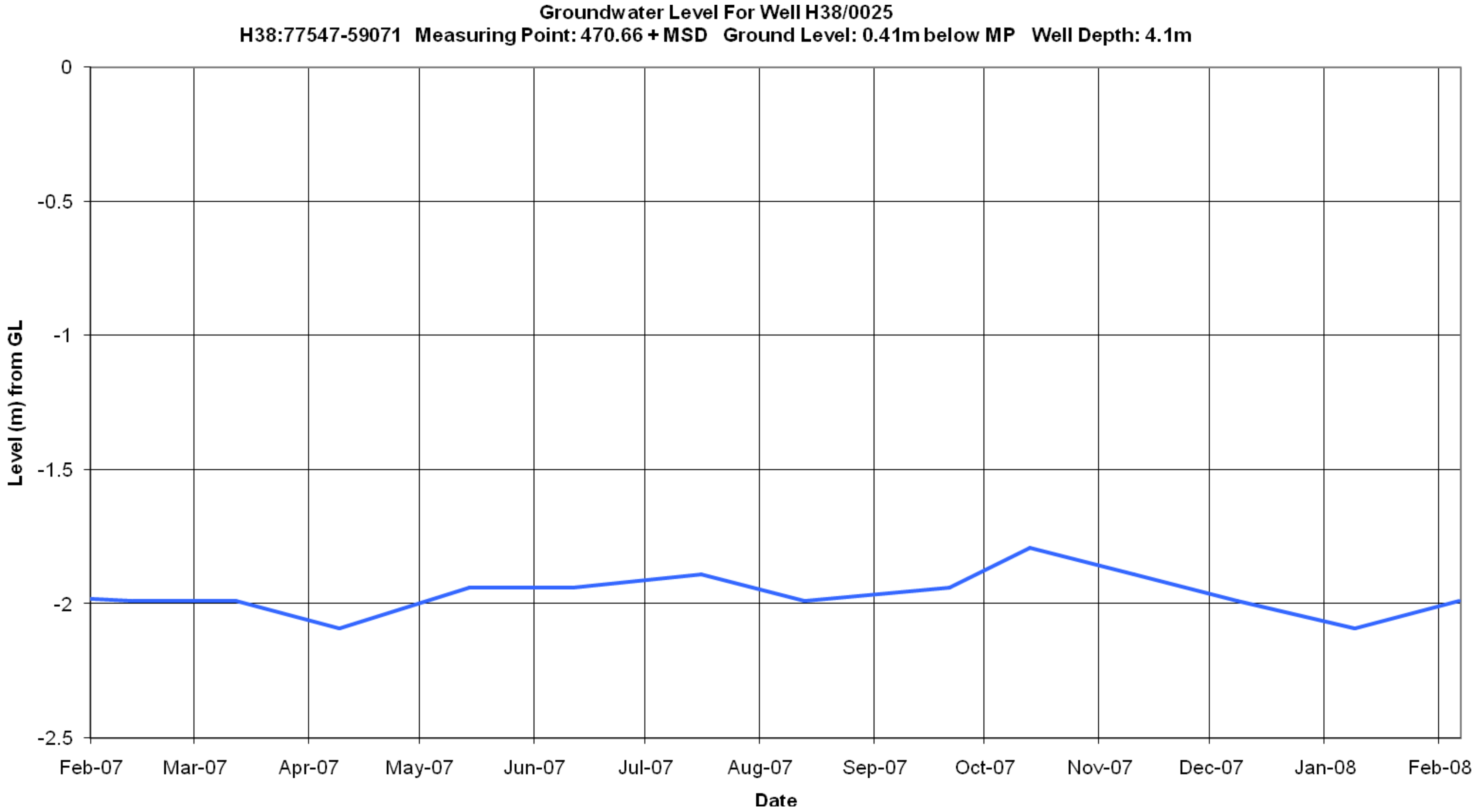
Groundwater Level For Well H38/0012
H38:77924-59271 Measuring Point: 471.58 + MSD Ground Level: 0.50m below MP Well Depth: 4.5m
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

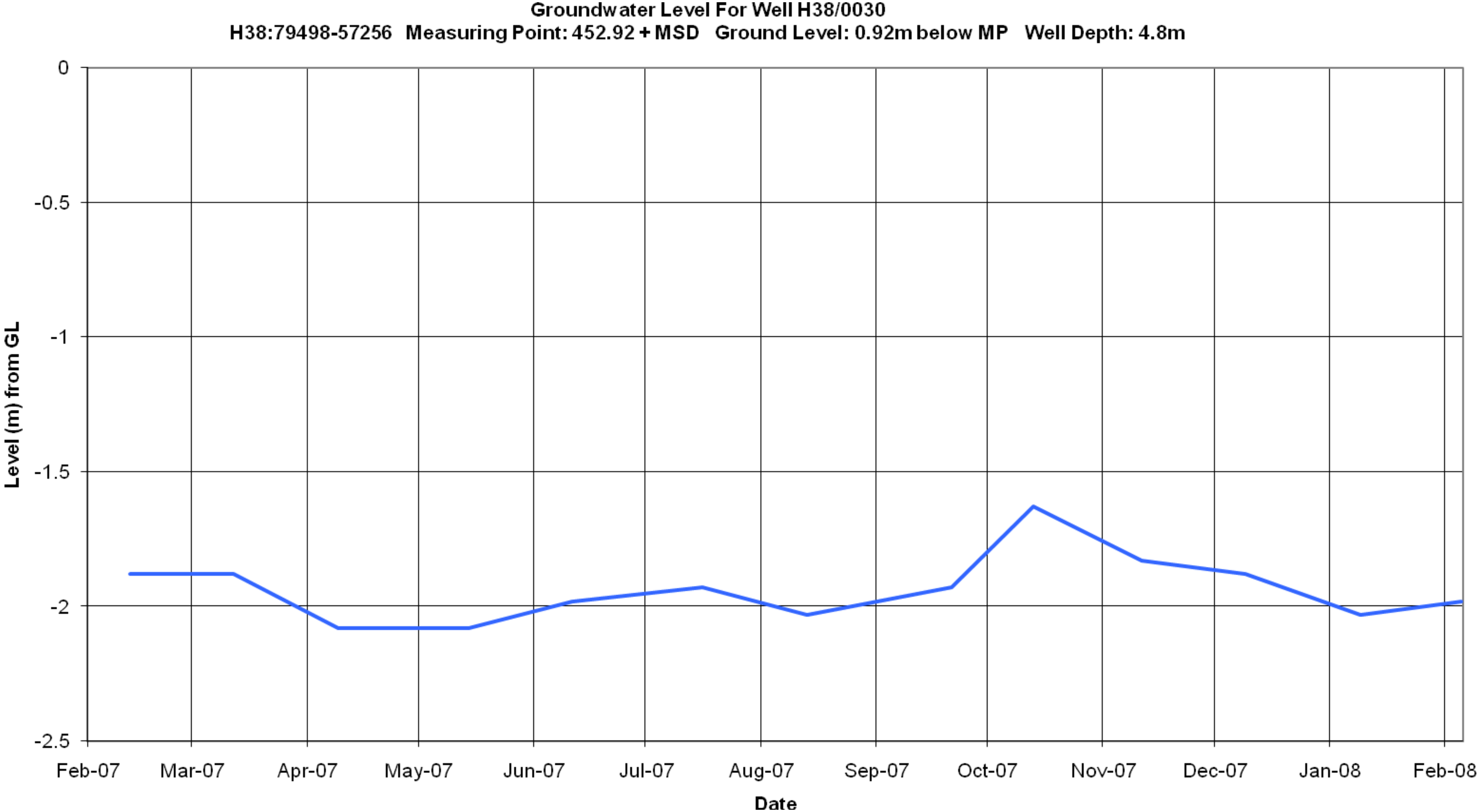

Groundwater Level For Well H38/0013
H38:75169-58386 Measuring Point: 496.80 + MSD Ground Level: 0.29m below MP Well Depth: 20.9m
Level (m) from GL
-15.5
-16
-16.5
-17
-17.5
-18
-18.5
-19
-19.5
-20
-20.5
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

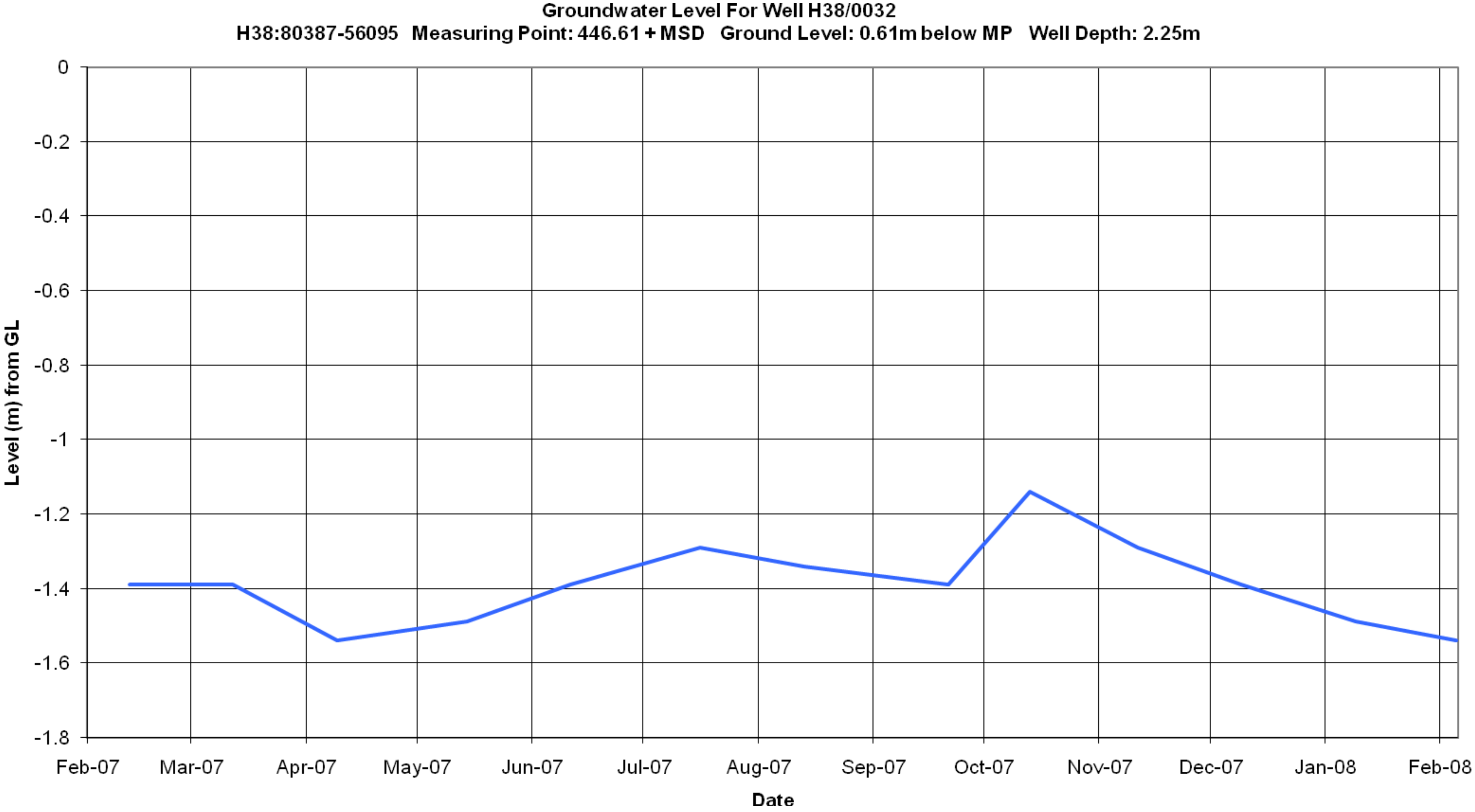

Groundwater Level For Well H38/0016
H38: 76730-56096 Measuring Point: 476.63 + MSD Ground Level: 0.30m below MP Well Depth: 29.7m
-24.5
-25
-25.5
-26
-26.5
-27
-27.5
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level For Well H38/0021
H38:79518-58092 Measuring Point: 459.07 + MSD Ground Level: 0.45m below MP Well Depth: 11.8m
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

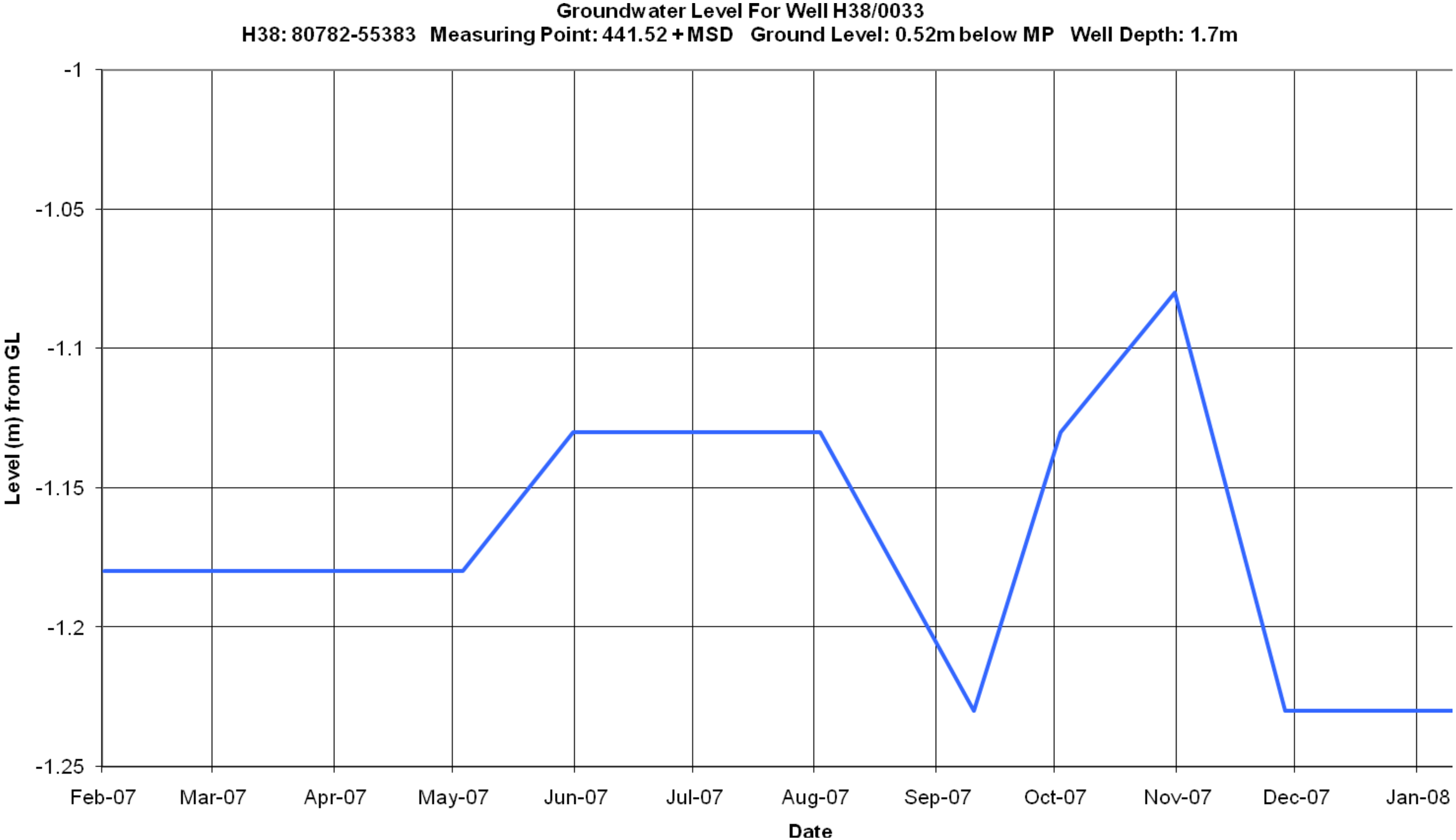

Groundwater Level For Well H38/0022
H38:79518-58184 Measuring Point: 459.26 + MSD Ground Level: 0.0m below MP Well Depth: 4.9m
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Level (m) from GL
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level For Well H38/0025
H38:77547-59071 Measuring Point: 470.66 + MSD Ground Level: 0.41m below MP Well Depth: 4.1m
0
-0.5
-1
-1.5
-2
-2.5
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

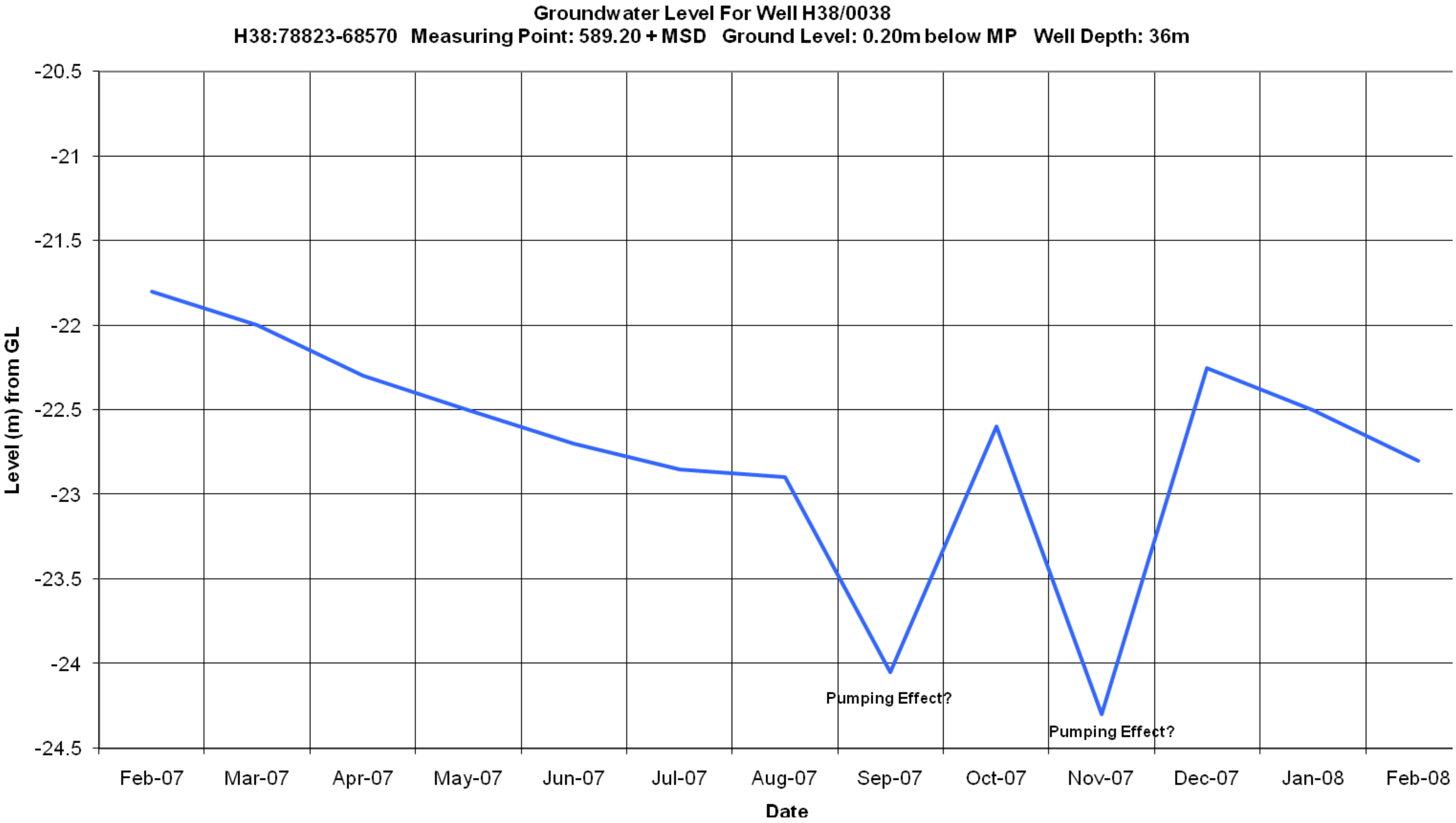

Groundwater Level For Well H38/0030
H38:79498-57256 Measuring Point: 452.92 + MSD Ground Level: 0.92m below MP Well Depth: 4.8m
Level (m) from GL
0
-0.5
-1
-1.5
-2
-2.5
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date



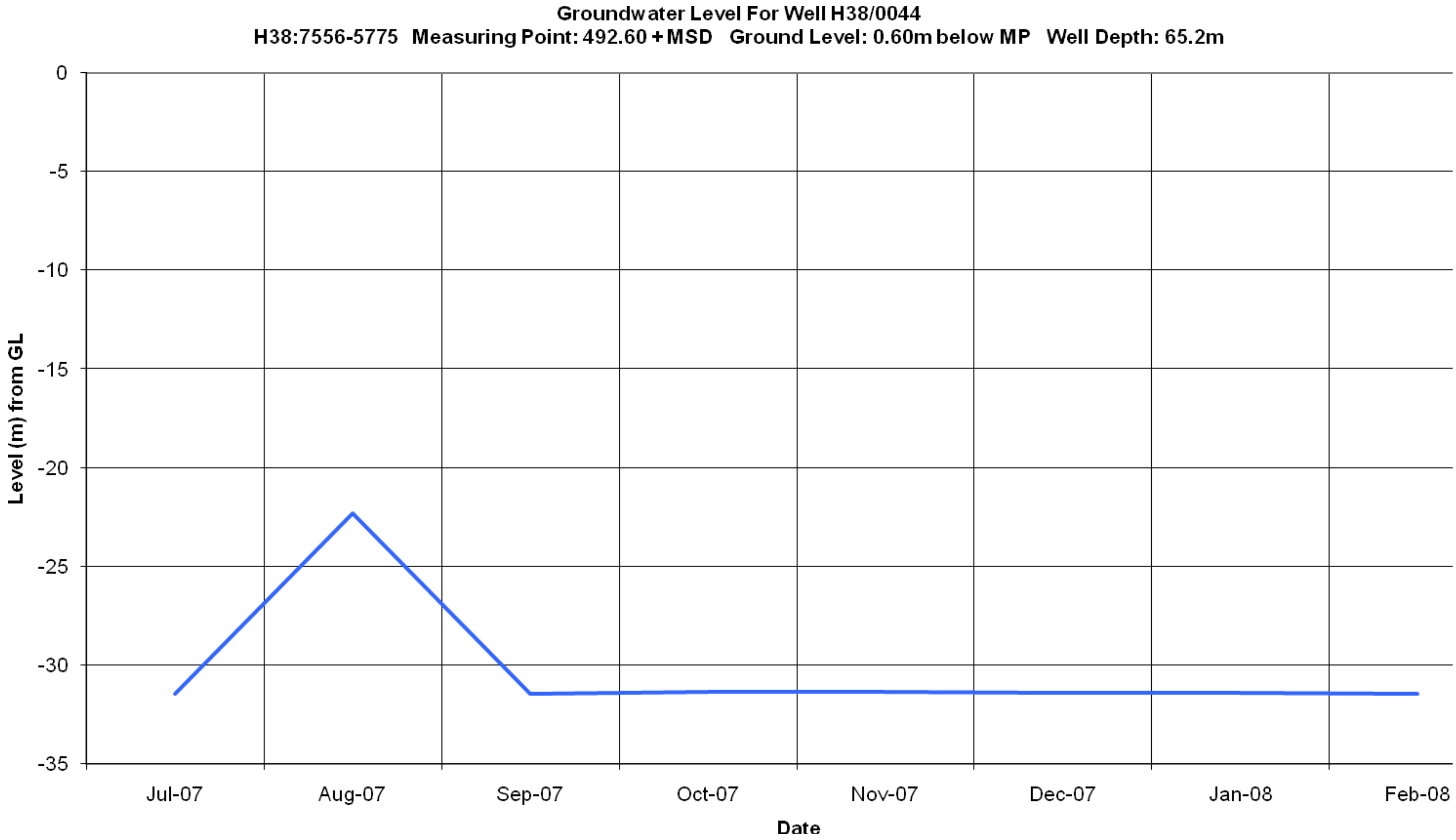
Groundwater Level For Well H38/0032
H38:80387-56095 Measuring Point: 446.61 + MSD Ground Level: 0.61m below MP Well Depth: 2.25m
Level (m) from GL
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

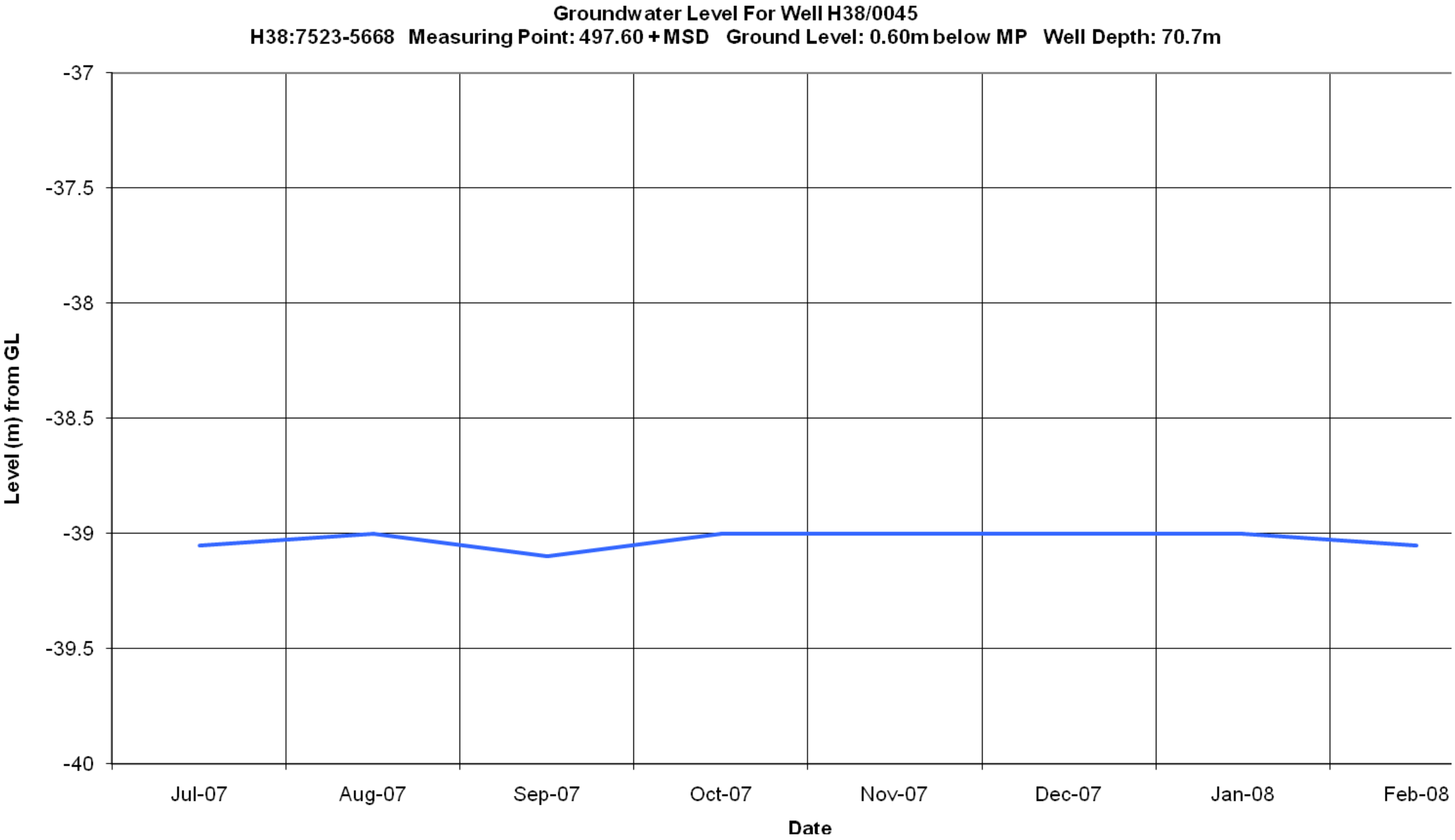


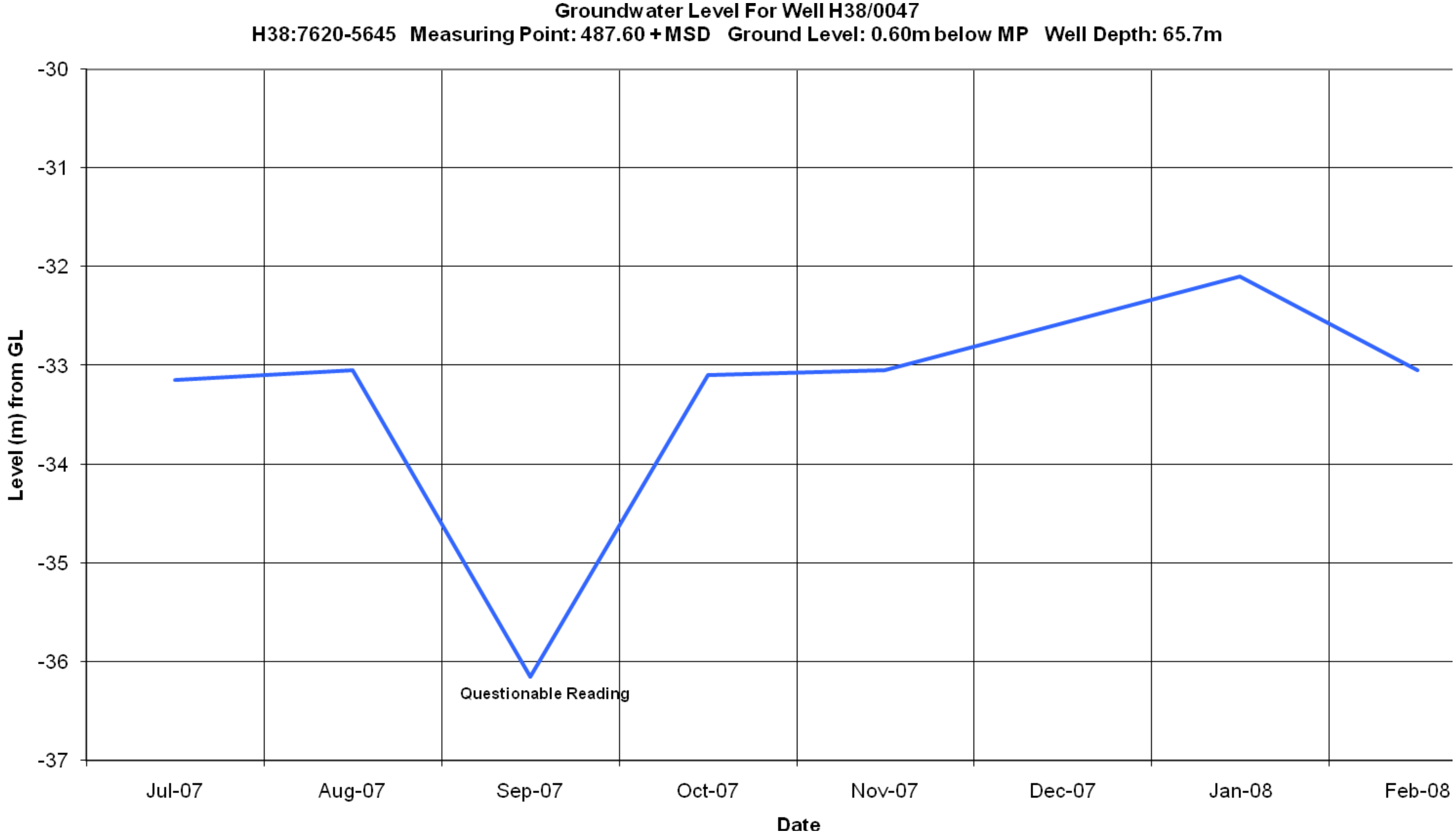
Groundwater Level For Well H38/0033
H38: 80782-55383 Measuring Point: 441.52 + MSD Ground Level: 0.52m below MP Well Depth: 1.7m
-1
-1.05
-1.1
-1.15
-1.2
-1.25
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Date

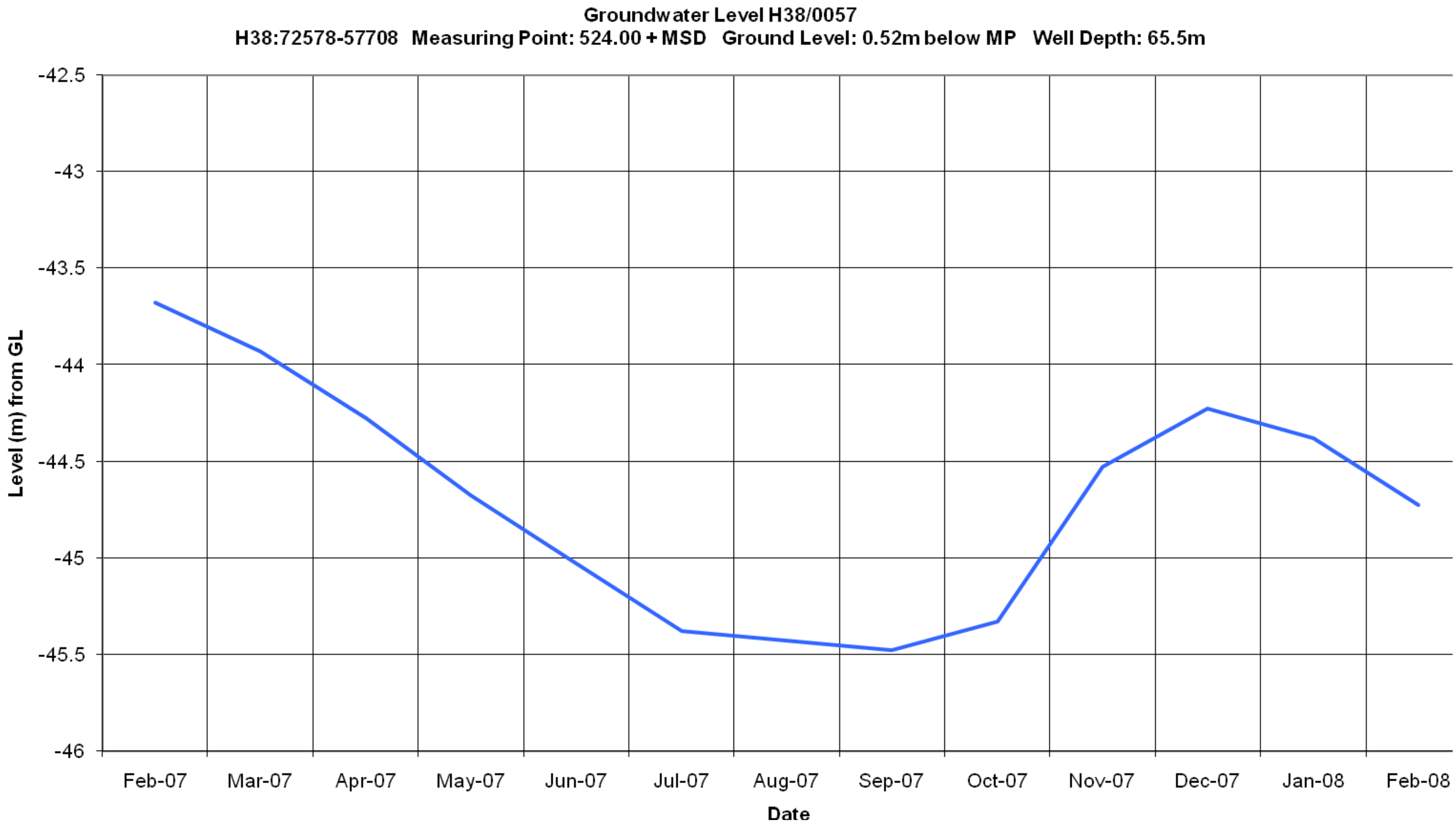


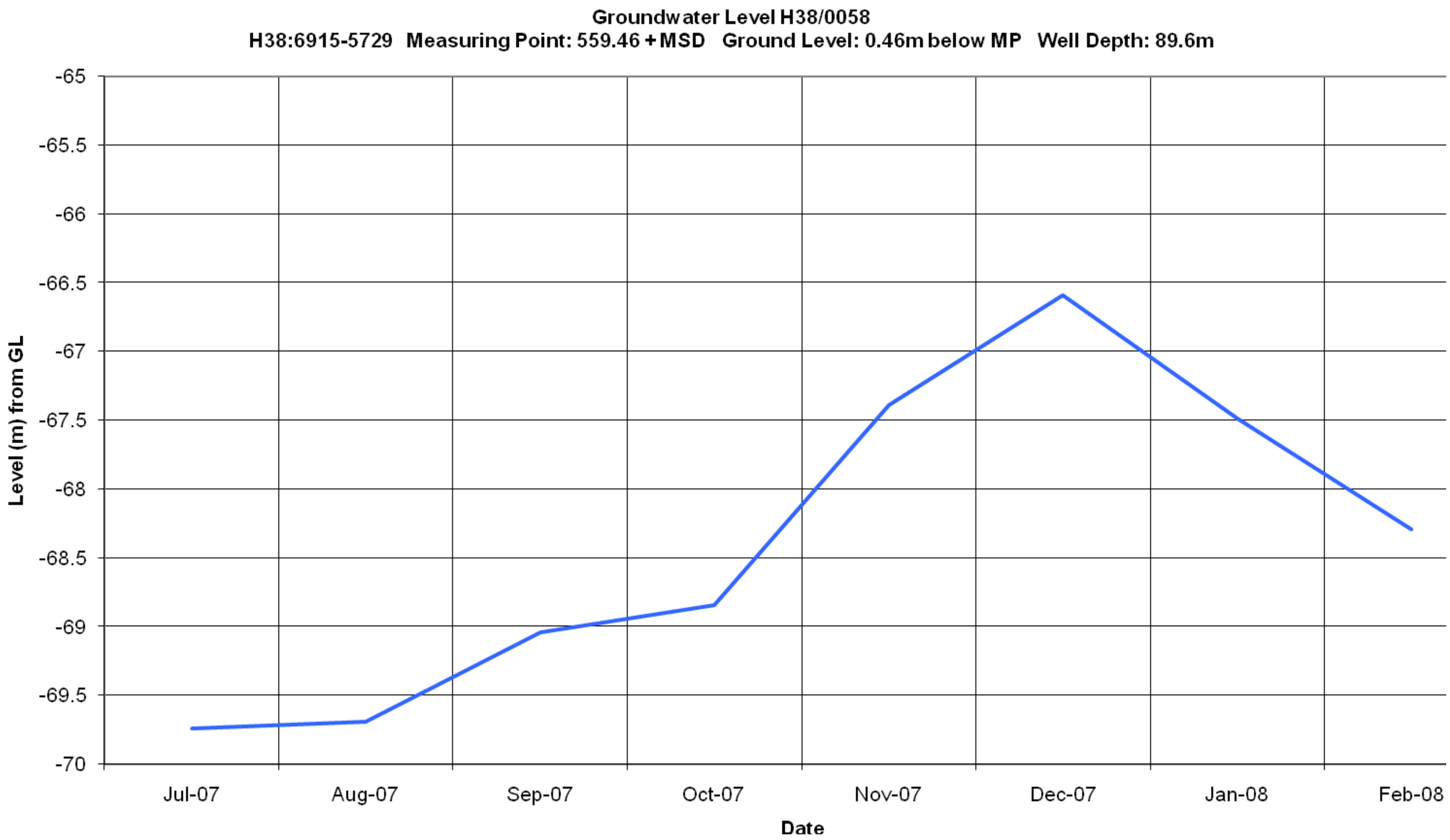
Groundwater Level For Well H38/0038
H38:78823-68570 Measuring Point: 589.20 + MSD Ground Level: 0.20m below MP Well Depth: 36m
-20.5
-21
-21.5
-22
-22.5
-23
-23.5
-24
-24.5
Level (m) from GL
Pumping Effect?
Pumping Effect?
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

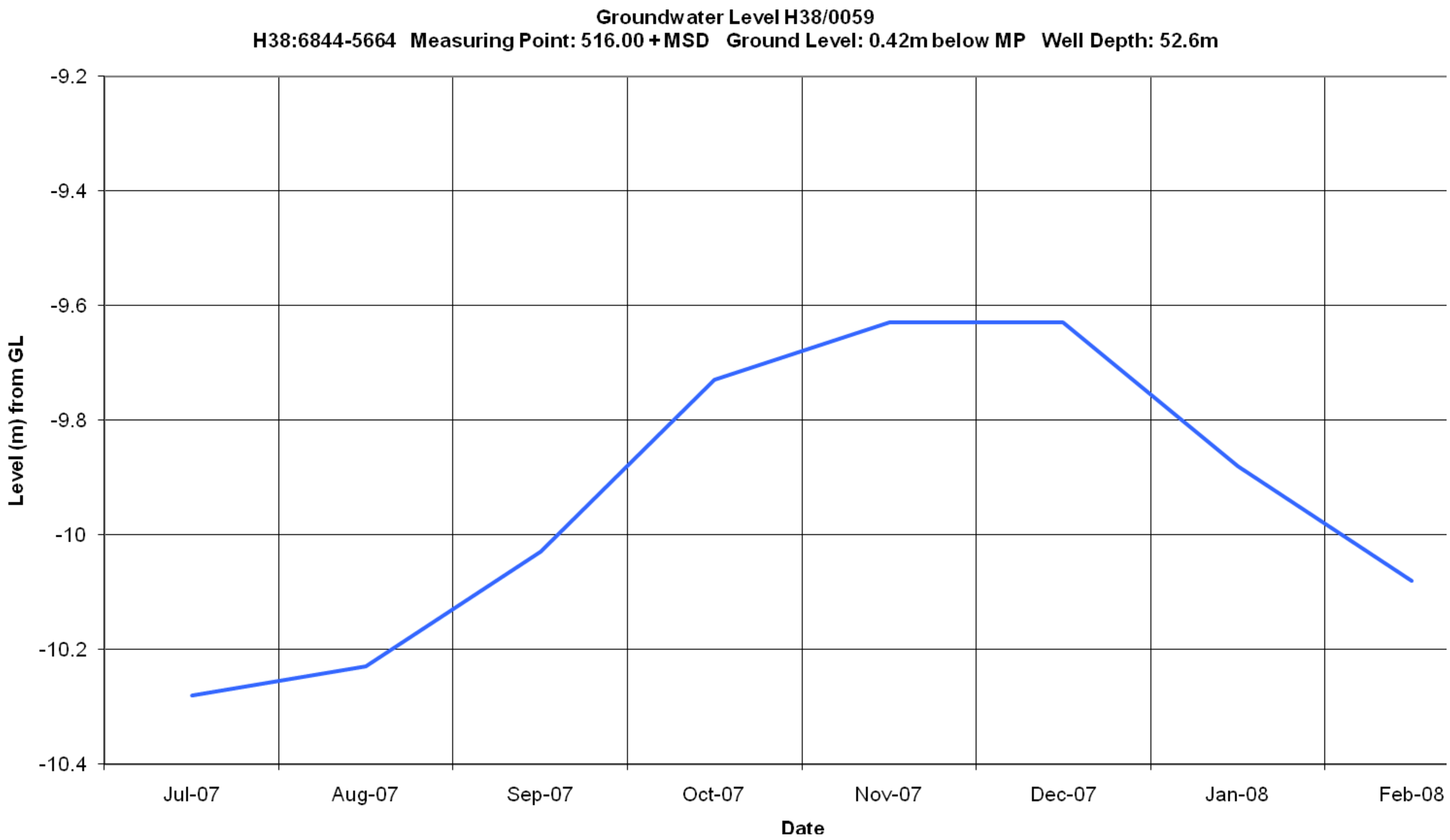

Groundwater Level For Well H38/0044
H38:7556-5775 Measuring Point: 492.60 + MSD Ground Level: 0.60m below MP Well Depth: 65.2m
0
-5
-10
-15
-20
-25
-30
-35
Level (m) from GL
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level For Well H38/0045
H38:7523-5668 Measuring Point: 497.60 +MSD Ground Level: 0.60m below MP Well Depth: 70.7m
-37
-37.5
-38
-38.5
-39
-39.5
-40
Level (m) from GL
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

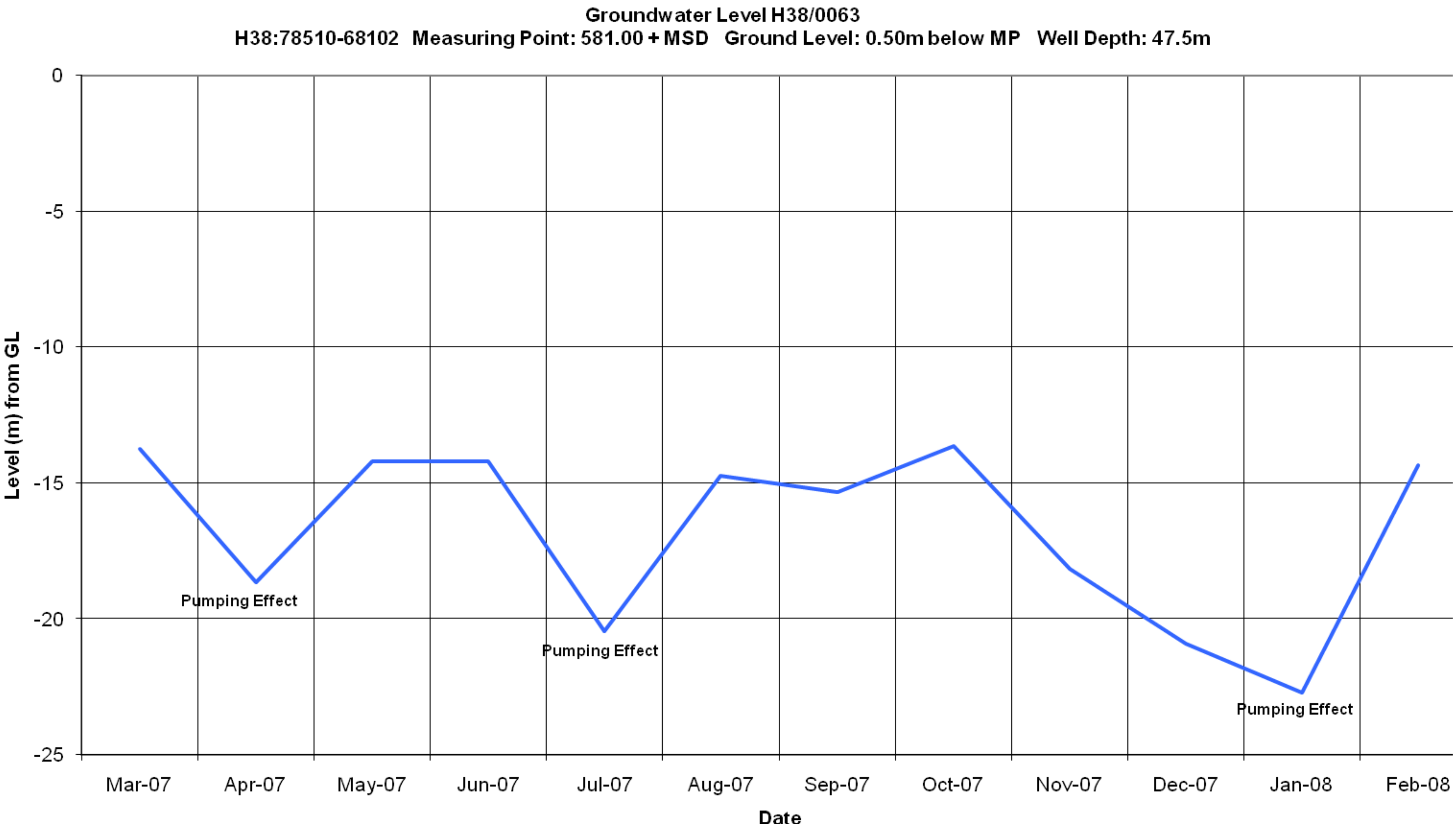

Groundwater Level For Well H38/0047
H38:7620-5645 Measuring Point: 487.60 + MSD Ground Level: 0.60m below MP Well Depth: 65.7m
Level (m) from GL
-30
-31
-32
-33
-34
-35
-36
-37
Questionable Reading
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

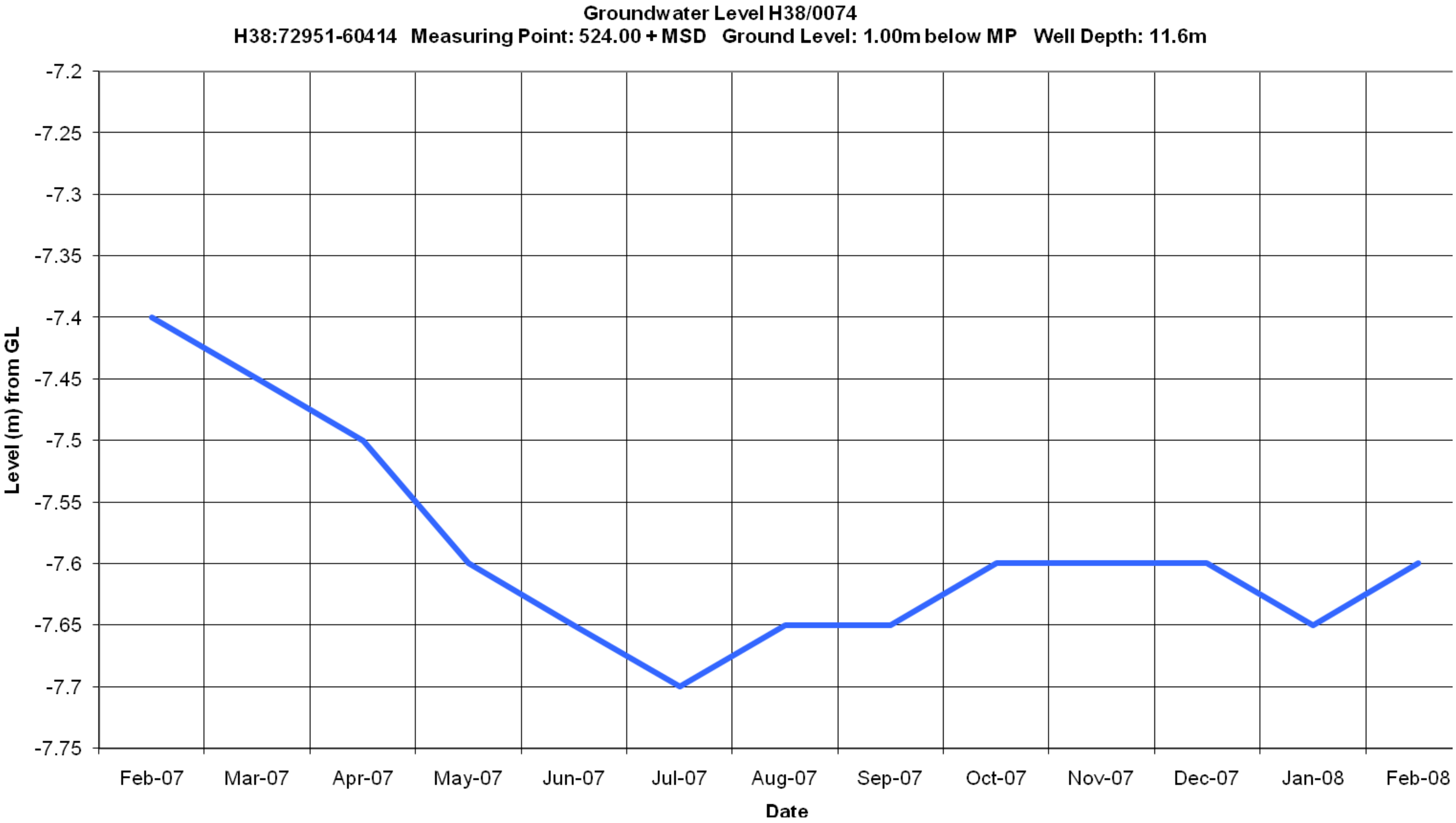

Groundwater Level H38/0057
H38:72578-57708 Measuring Point: 524.00 + MSD Ground Level: 0.52m below MP Well Depth: 65.5m
-42.5
-43
-43.5
-44
-44.5
-45
-45.5
-46
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

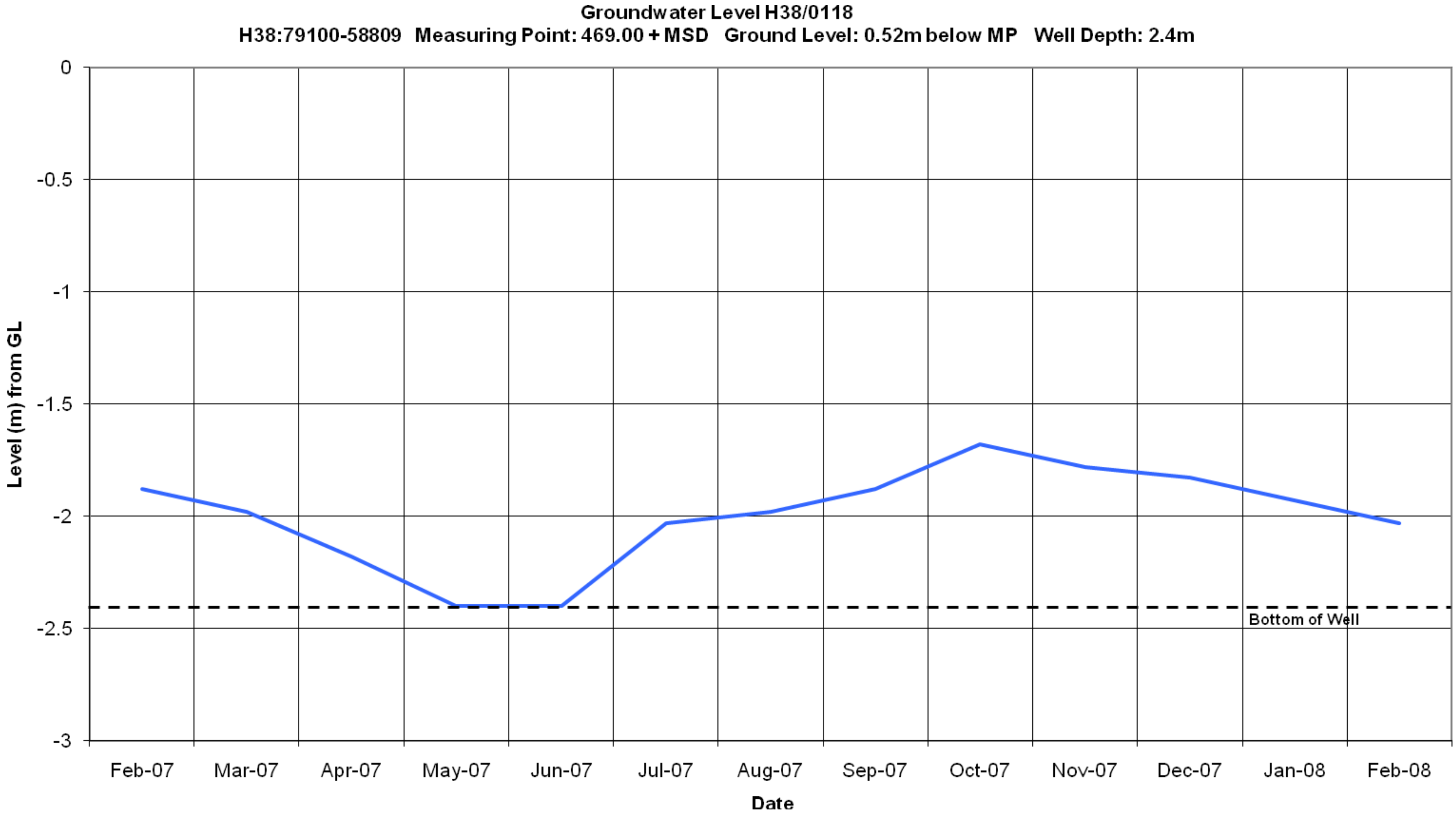

Groundwater Level H38/0058
H38:6915-5729 Measuring Point: 559.46 +MSD Ground Level: 0.46m below MP Well Depth: 89.6m
-65
-65.5
-66
-66.5
-67
-67.5
-68
-68.5
-69
-69.5
-70
Level (m) from GL
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date



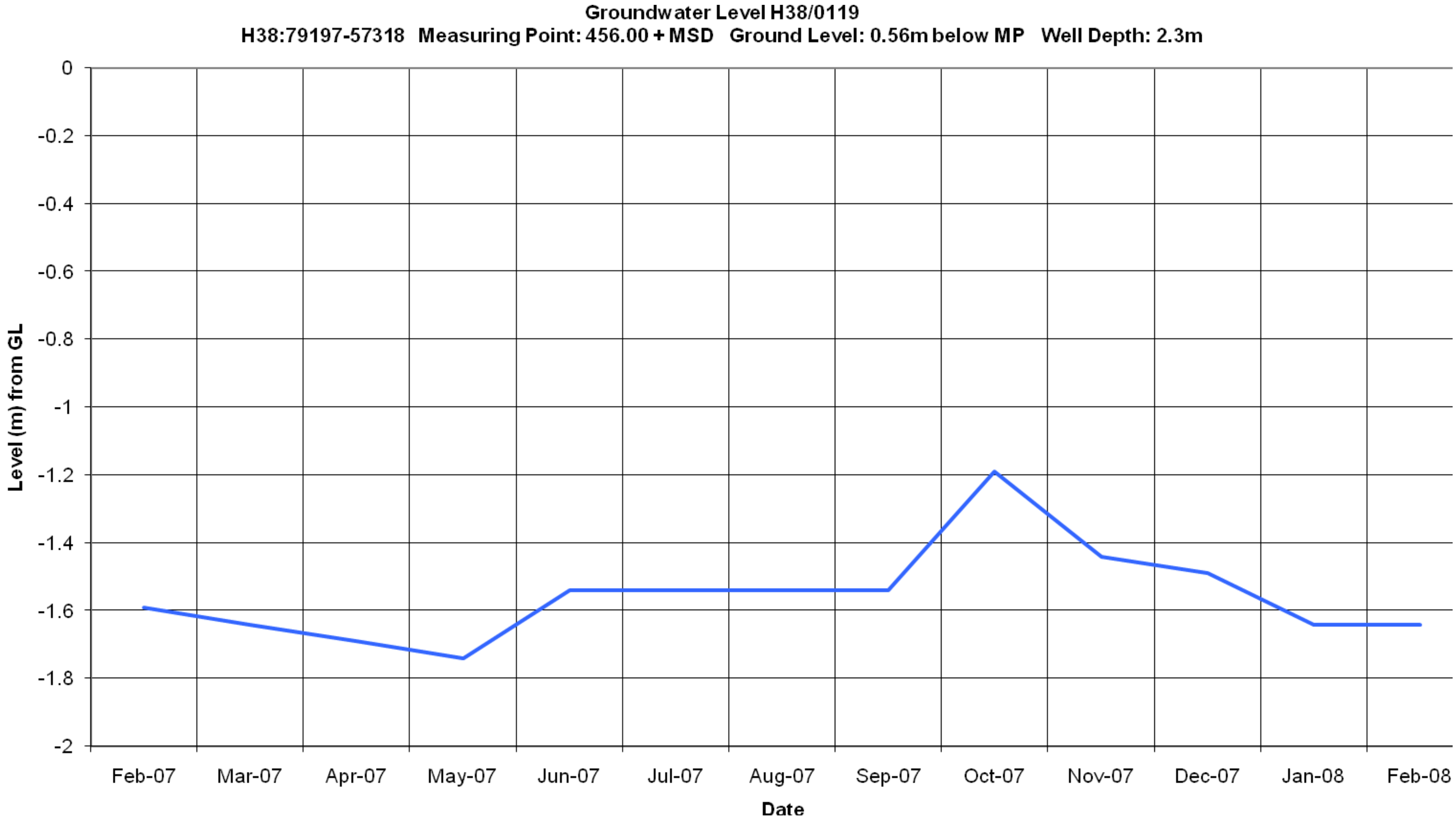
Groundwater Level H38/0059
H38:6844-5664 Measuring Point: 516.00 + MSD Ground Level: 0.42m below MP Well Depth: 52.6m
-9.2
-9.4
-9.6
-9.8
-10
-10.2
-10.4
Level (m) from GL
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

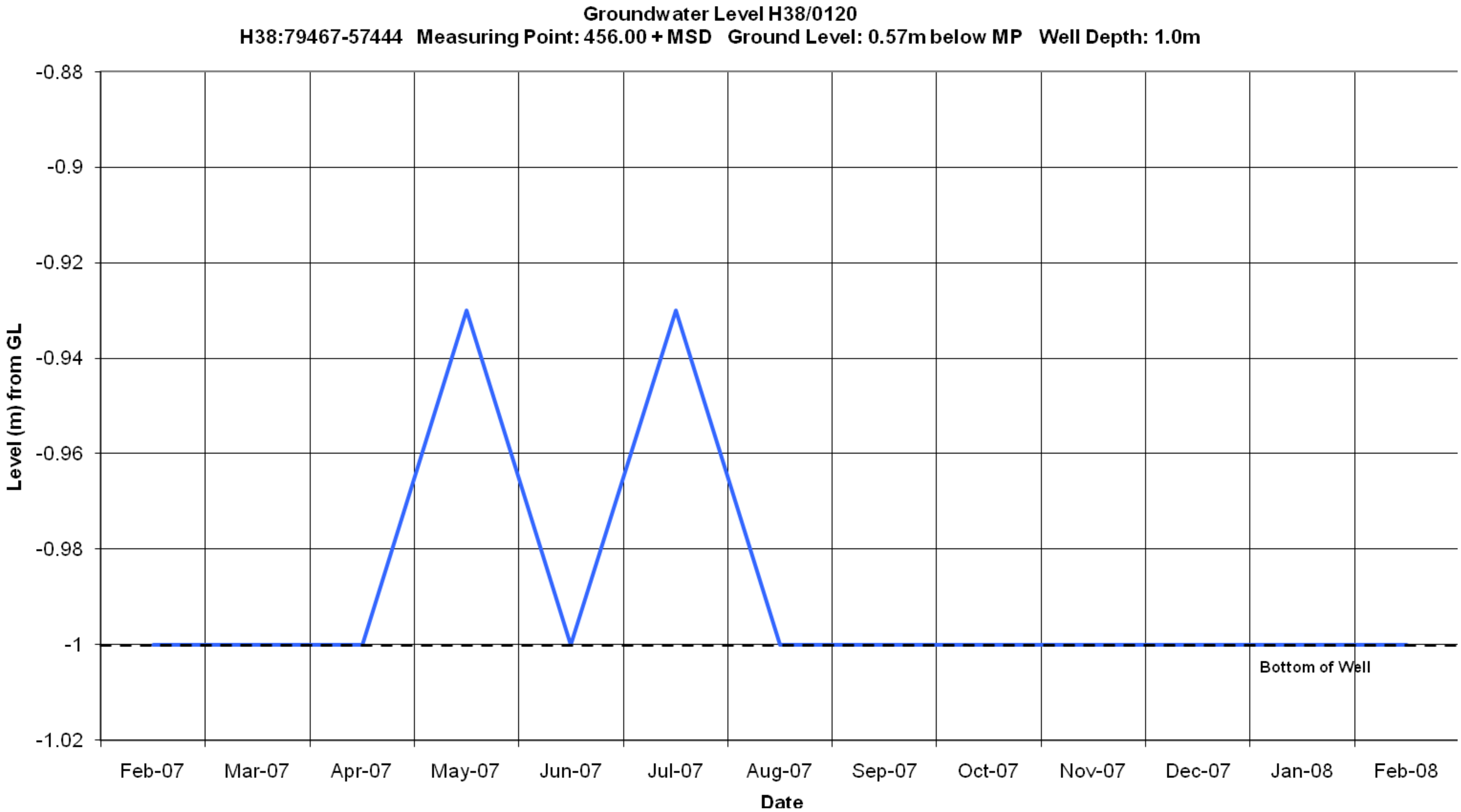

Groundwater Level H38/0063
H38:78510-68102 Measuring Point: 581.00 + MSD Ground Level: 0.50m below MP Well Depth: 47.5m
0
-5
-10
-15
-20
-25
Level (m) from GL
Pumping Effect
Pumping Effect
Pumping Effect
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level H38/0074
H38:72951-60414 Measuring Point: 524.00 + MSD Ground Level: 1.00m below MP Well Depth: 11.6m
Level (m) from GL
-7.2
-7.25
-7.3
-7.35
-7.4
-7.45
-7.5
-7.55
-7.6
-7.65
-7.7
-7.75
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

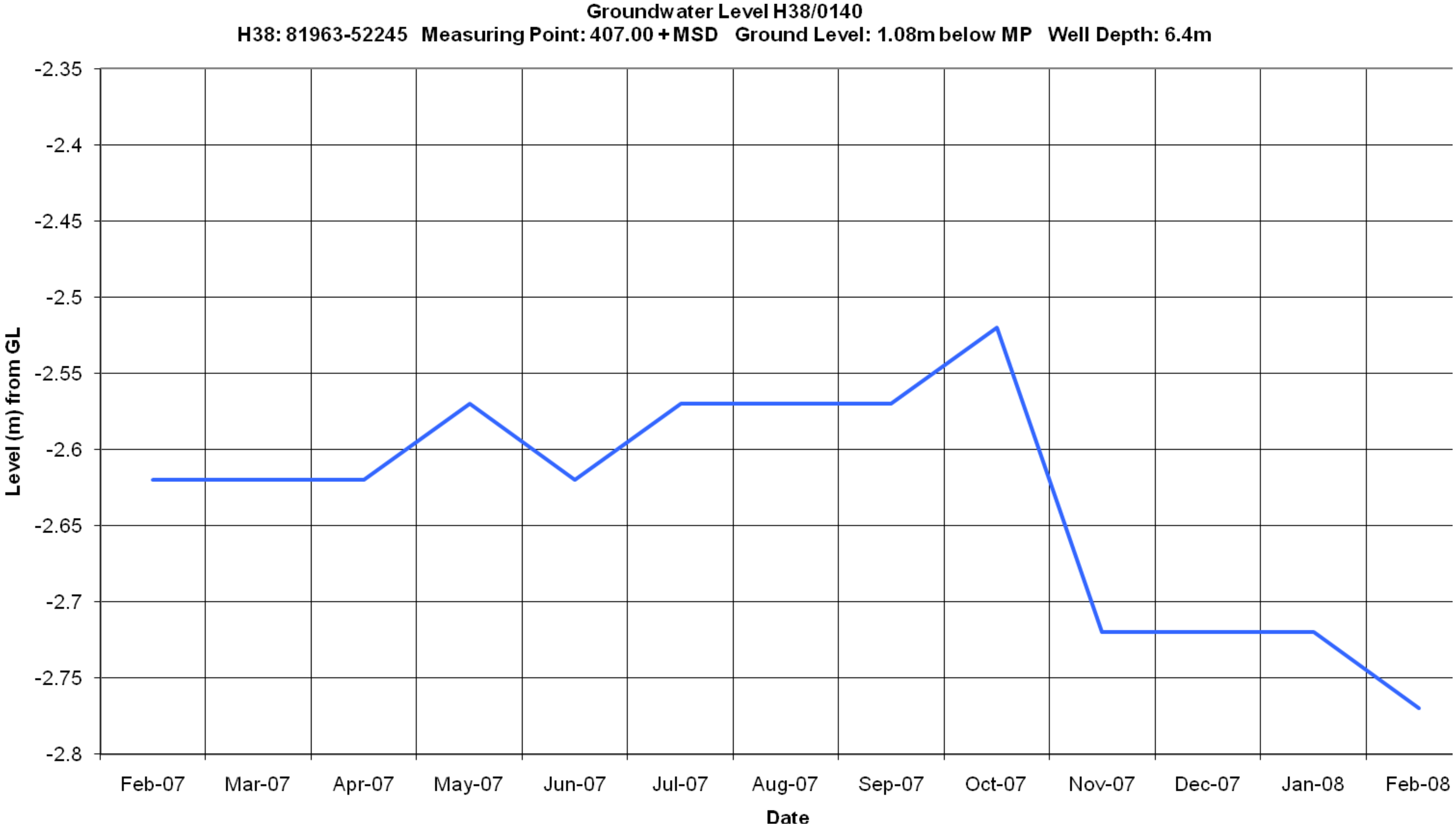


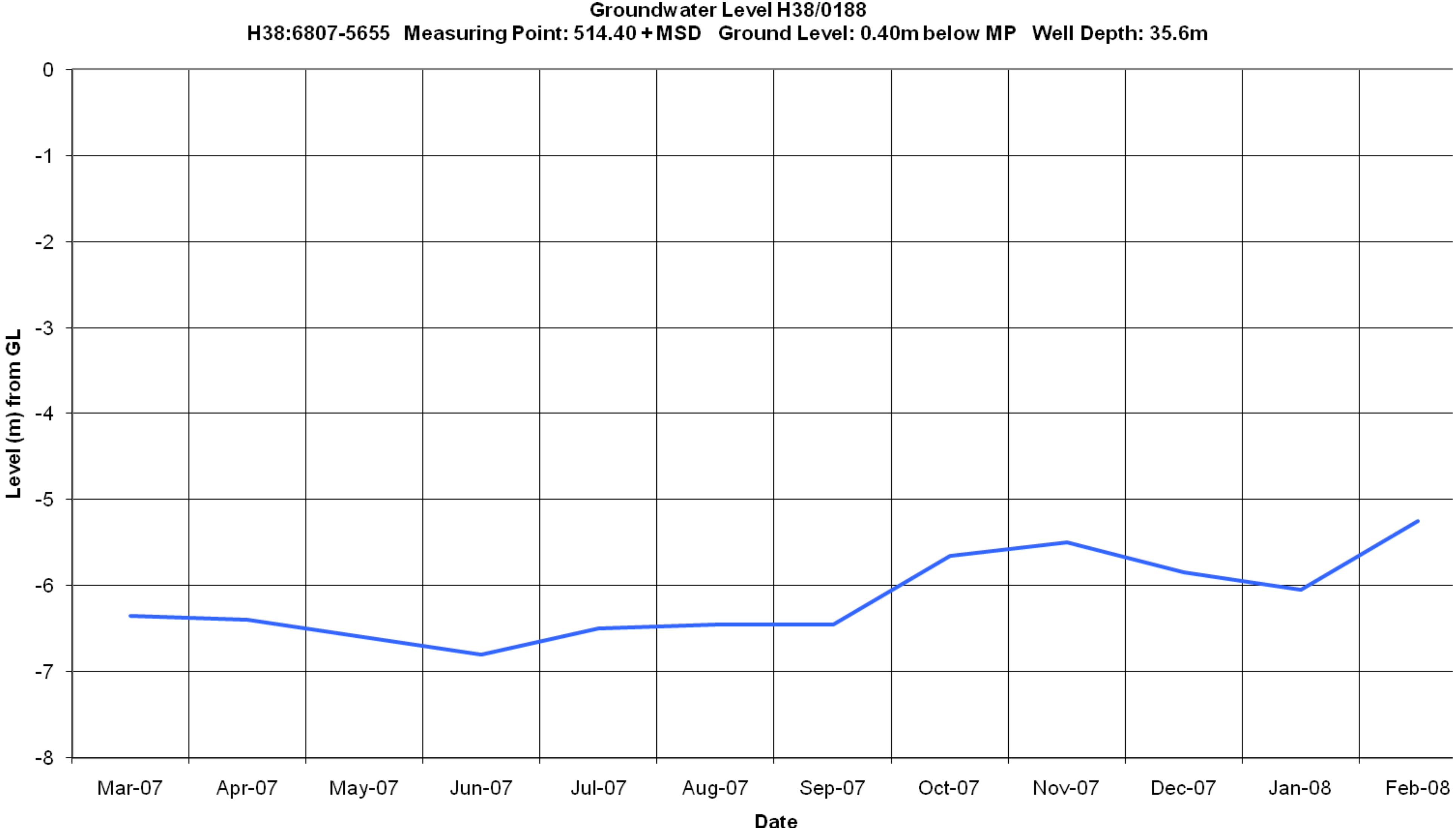
Groundwater Level H38/0118
H38:79100-58809 Measuring Point: 469.00 + MSD Ground Level: 0.52m below MP Well Depth: 2.4m
0
-0.5
-1
-1.5
-2
-2.5
-3
Level (m) from GL
Bottom of Well
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

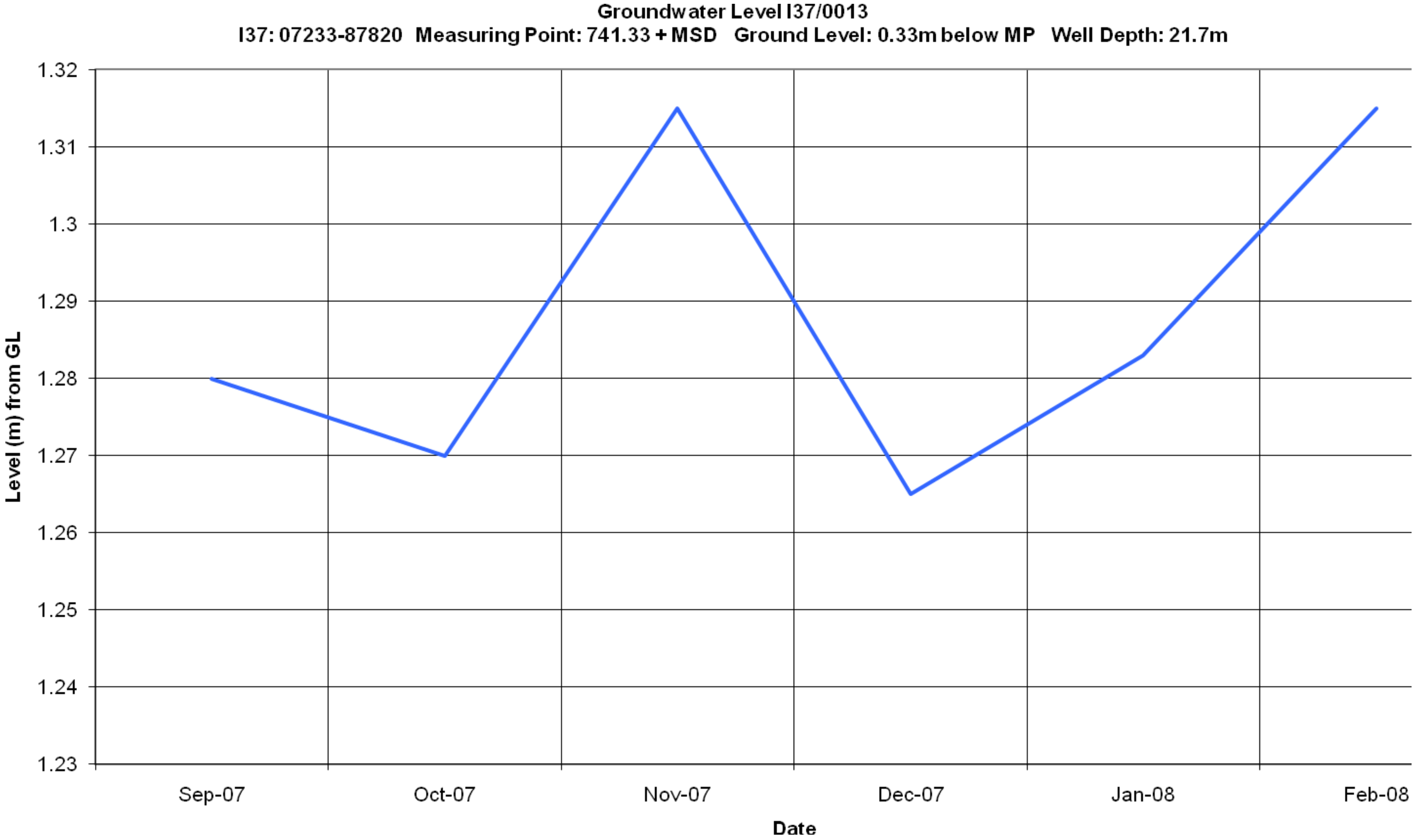

Groundwater Level H38/0119
H38:79197-57318 Measuring Point: 456.00 + MSD Ground Level: 0.56m below MP Well Depth: 2.3m
Level (m) from GL
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date



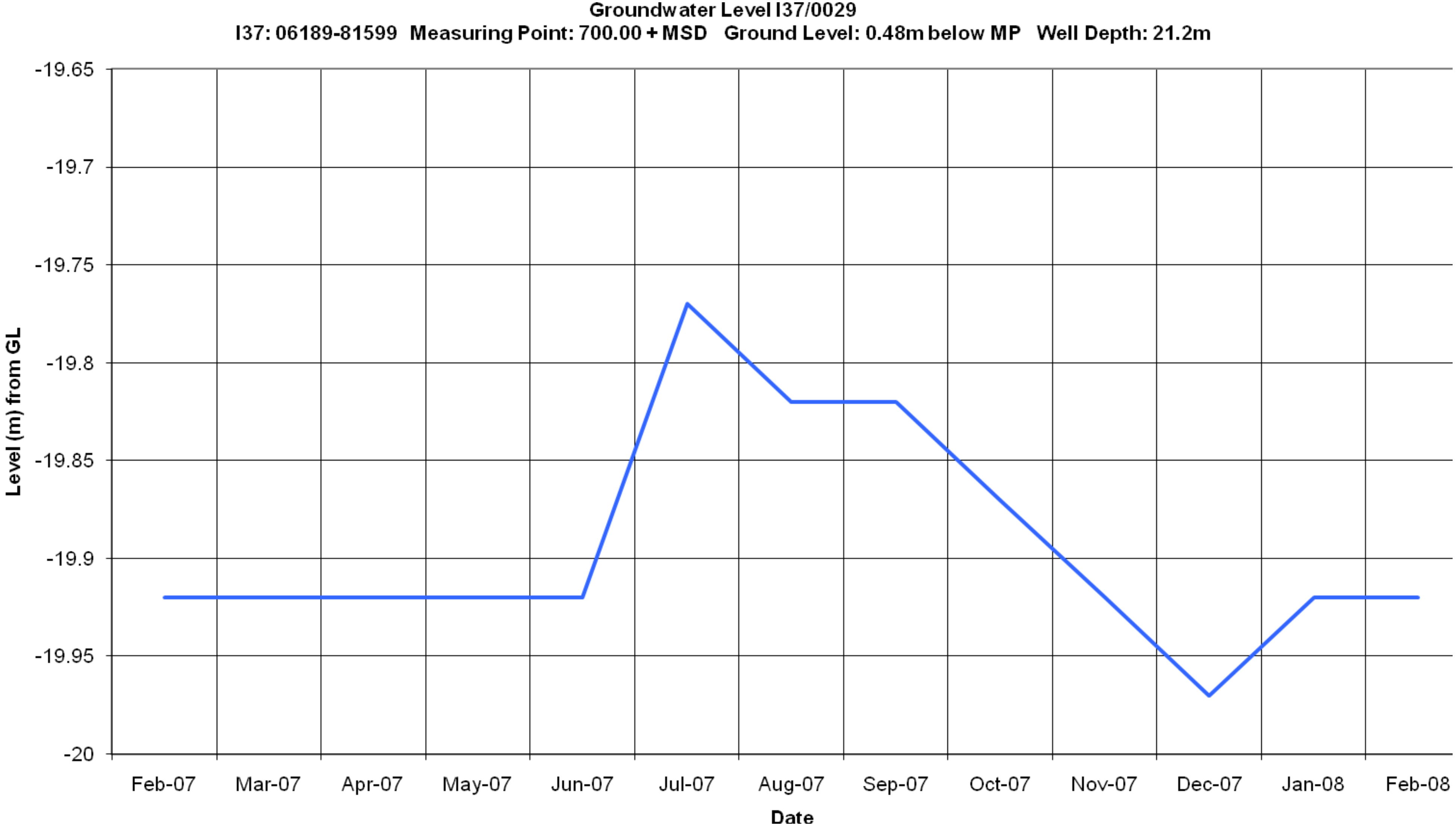
Groundwater Level H38/0120
H38:79467-57444 Measuring Point: 456.00 + MSD Ground Level: 0.57m below MP Well Depth: 1.0m
-0.88
-0.9
-0.92
-0.94
-0.96
-0.98
-1
-1.02
Level (m) from GL
Bottom of Well
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

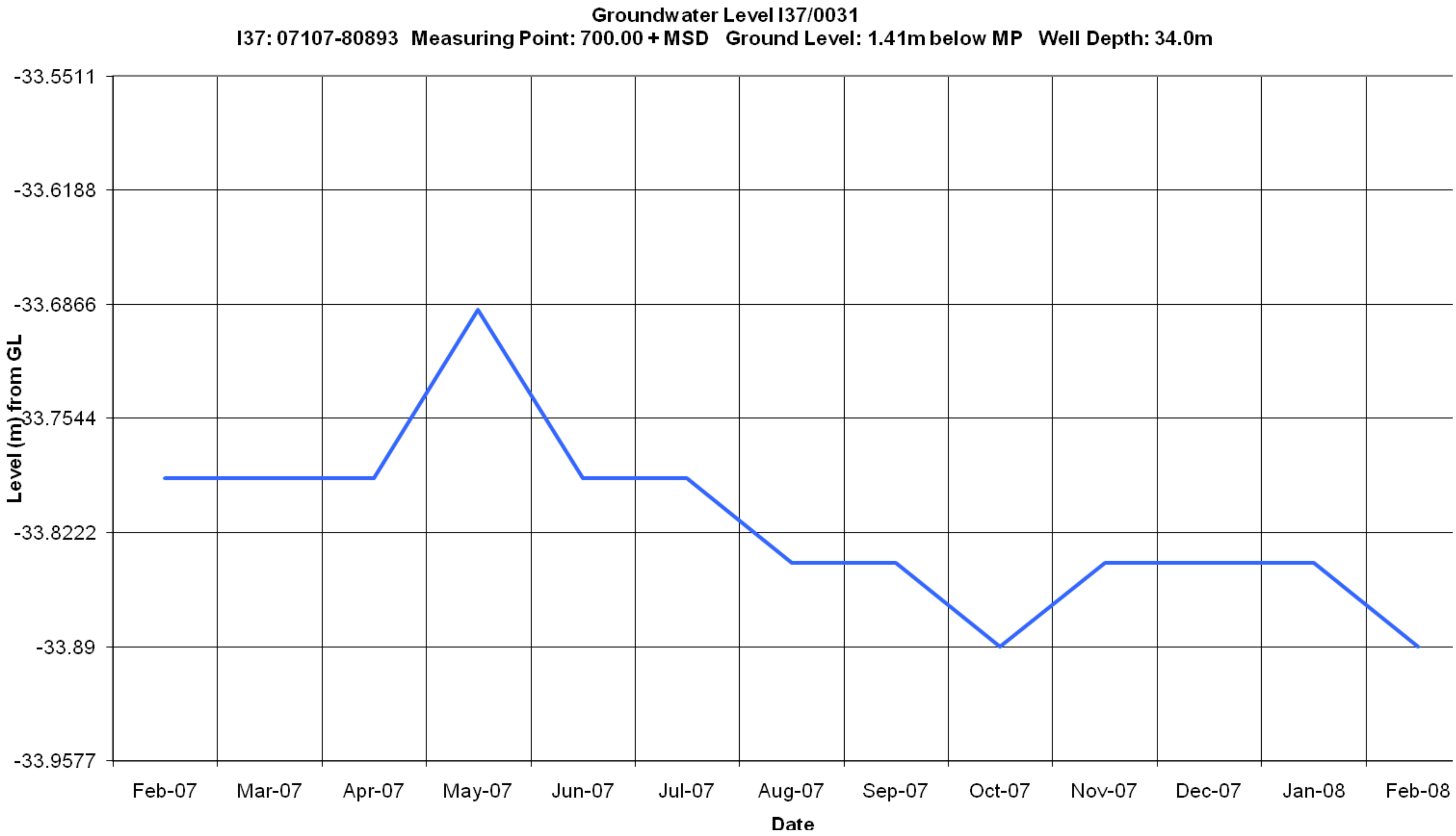

Groundwater Level H38/0140
H38: 81963-52245 Measuring Point: 407.00 + MSD Ground Level: 1.08m below MP Well Depth: 6.4m
Level (m) from GL
-2.35
-2.4
-2.45
-2.5
-2.55
-2.6
-2.65
-2.7
-2.75
-2.8
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

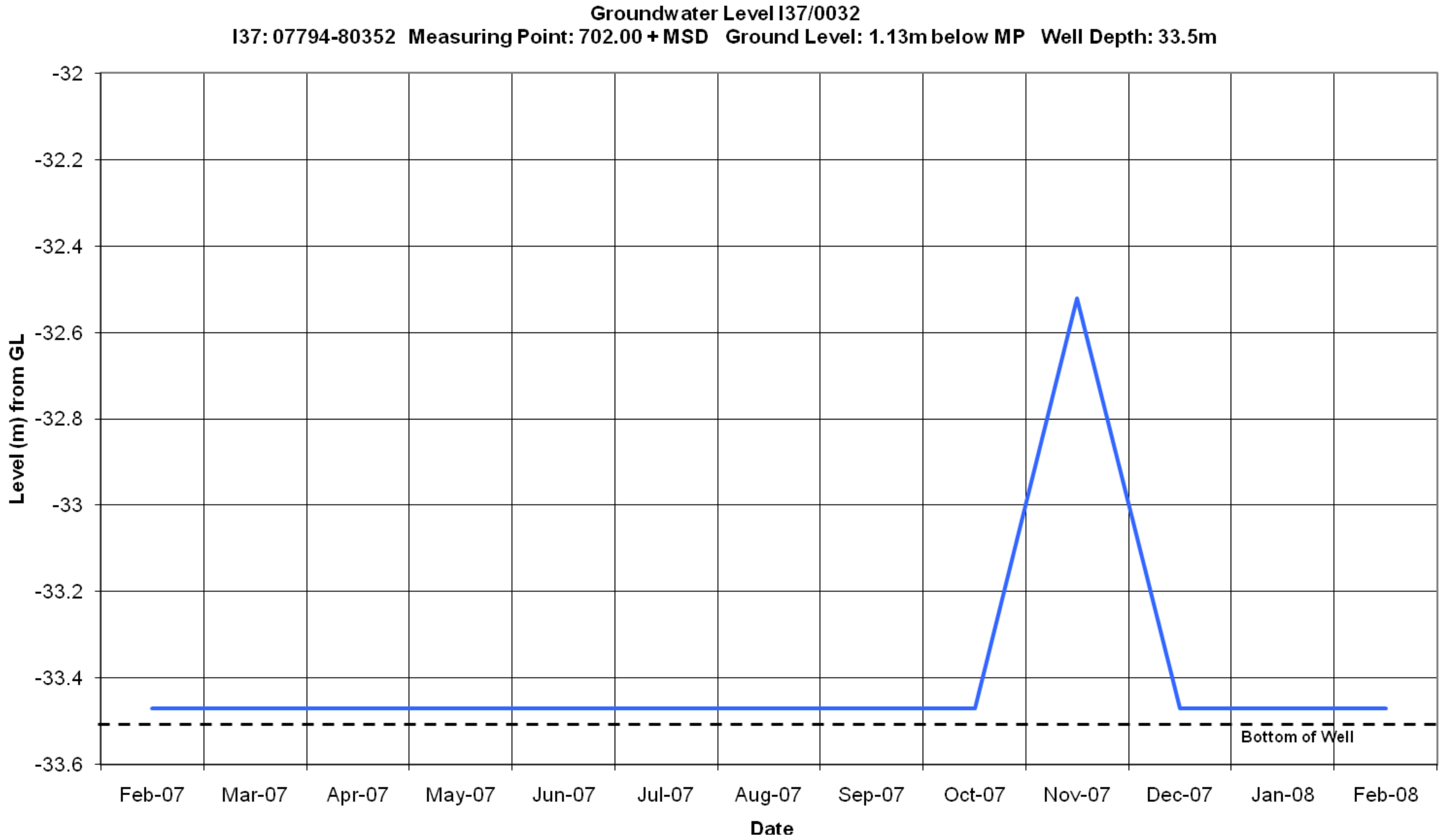

Groundwater Level H38/0188
H38:6807-5655 Measuring Point: 514.40 + MSD Ground Level: 0.40m below MP Well Depth: 35.6m
Level (m) from GL
0
-1
-2
-3
-4
-5
-6
-7
-8
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

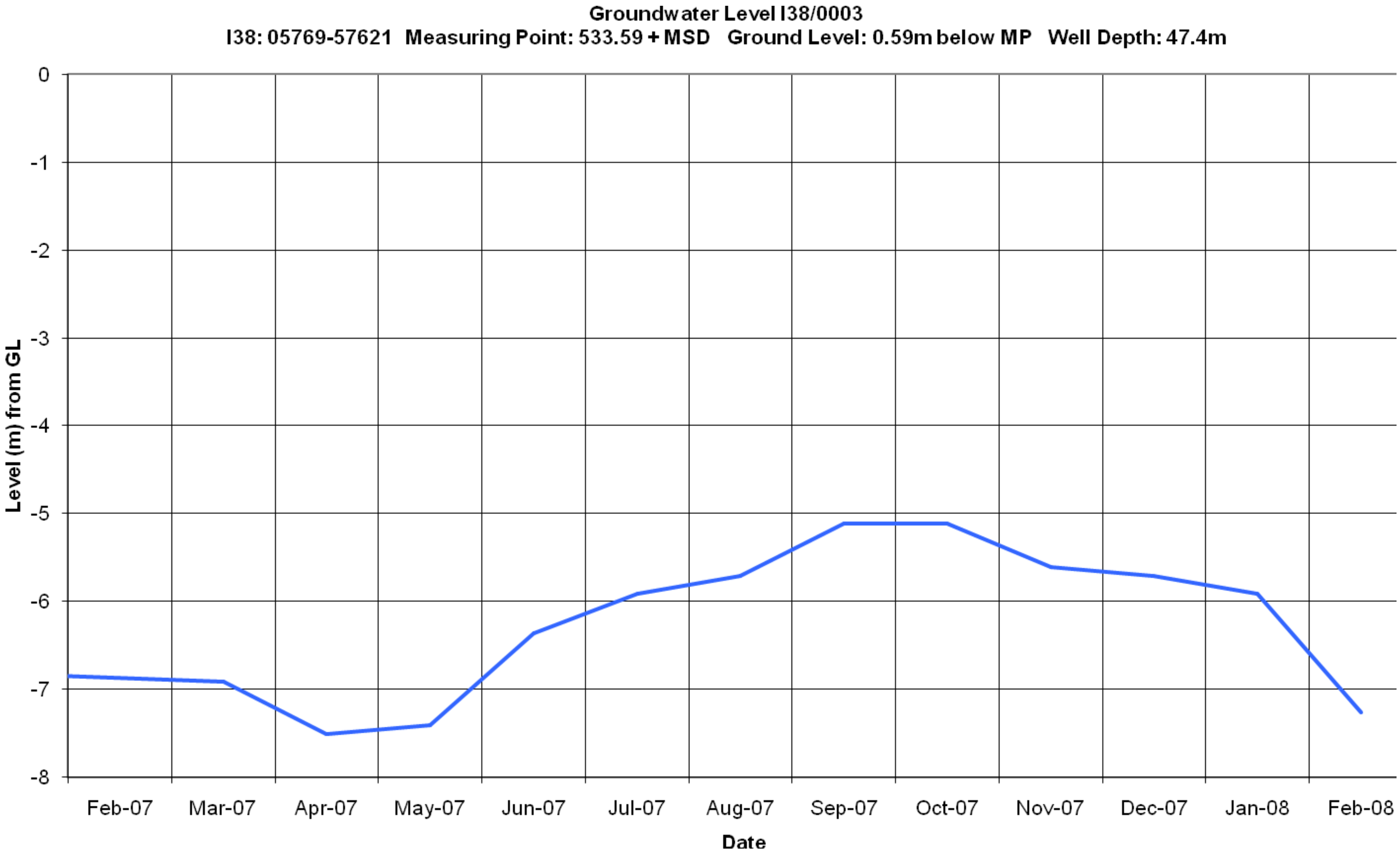


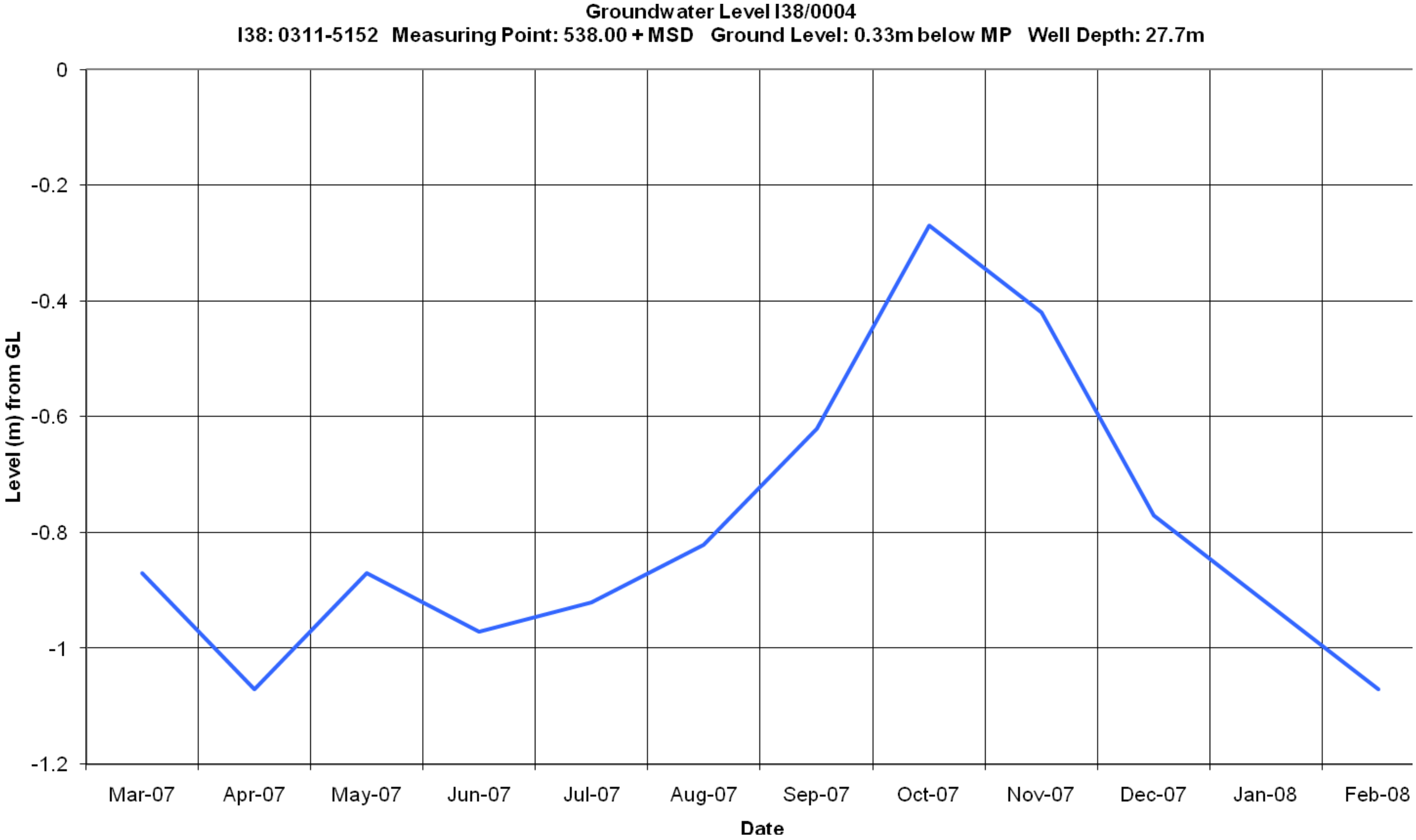
Groundwater Level I37/0013
I37: 07233-87820 Measuring Point: 741.33 + MSD Ground Level: 0.33m below MP Well Depth: 21.7m
1.32
1.31
1.3
1.29
1.28
1.27
1.26
1.25
1.24
1.23
Level (m) from GL
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

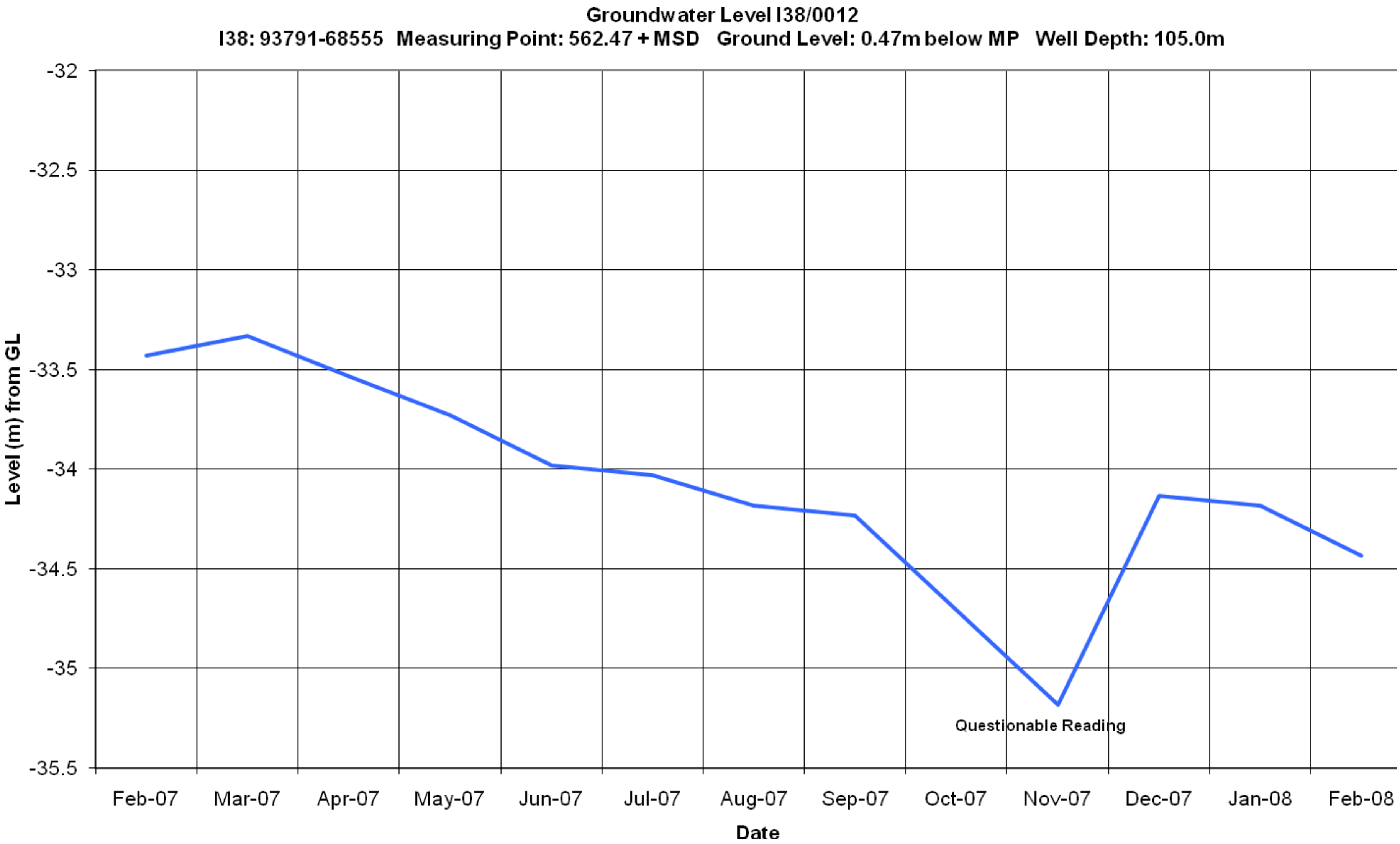

Groundwater Level I37/0029
I37: 06189-81599 Measuring Point: 700.00 + MSD Ground Level: 0.48m below MP Well Depth: 21.2m
-19.65
-19.7
-19.75
-19.8
-19.85
-19.9
-19.95
-20
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

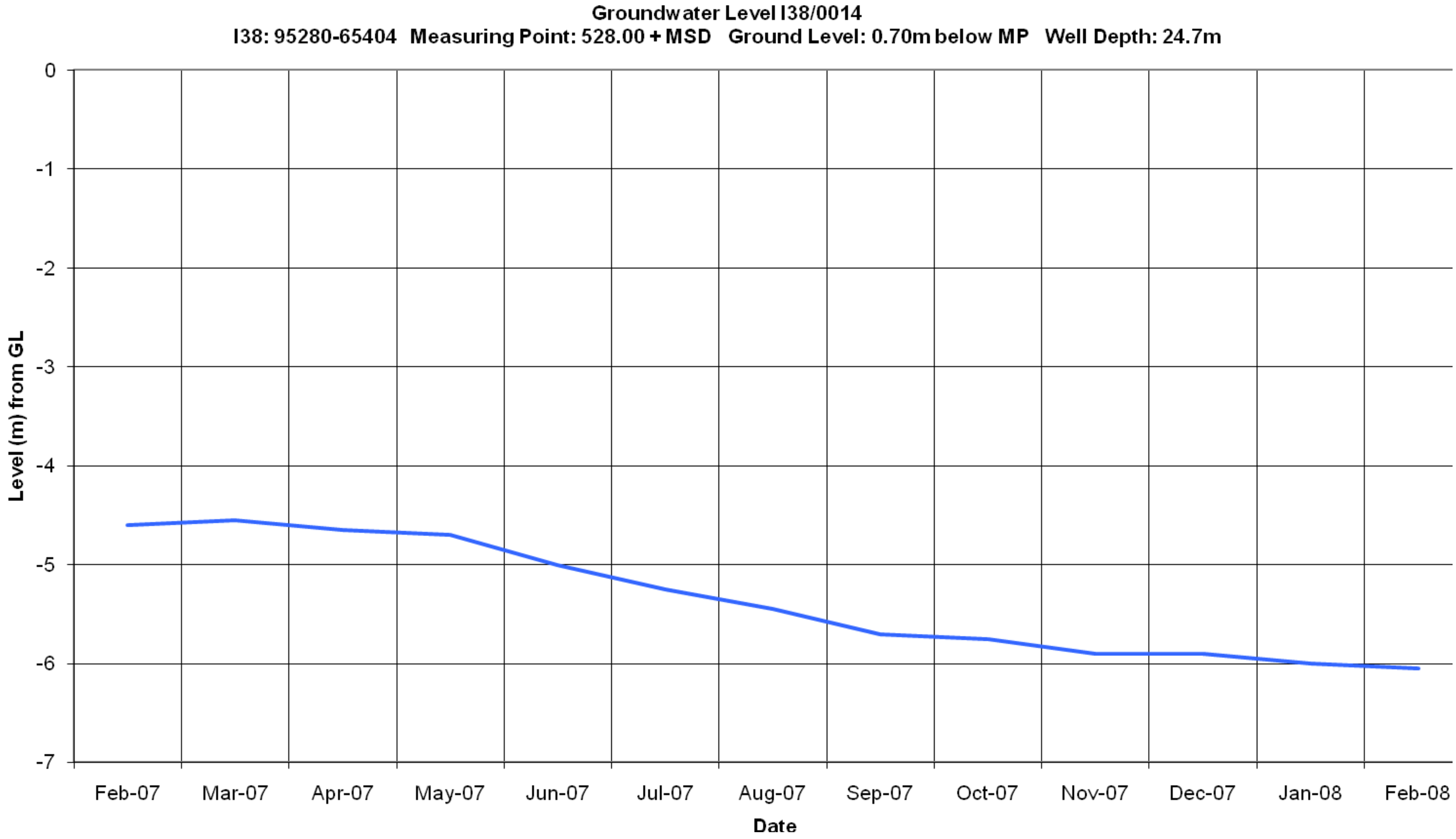

Groundwater Level I37/0031
I37: 07107-80893 Measuring Point: 700.00 + MSD Ground Level: 1.41m below MP Well Depth: 34.0m
-33.5511
-33.6188
-33.6866
-33.7544
-33.8222
-33.89
-33.9577
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

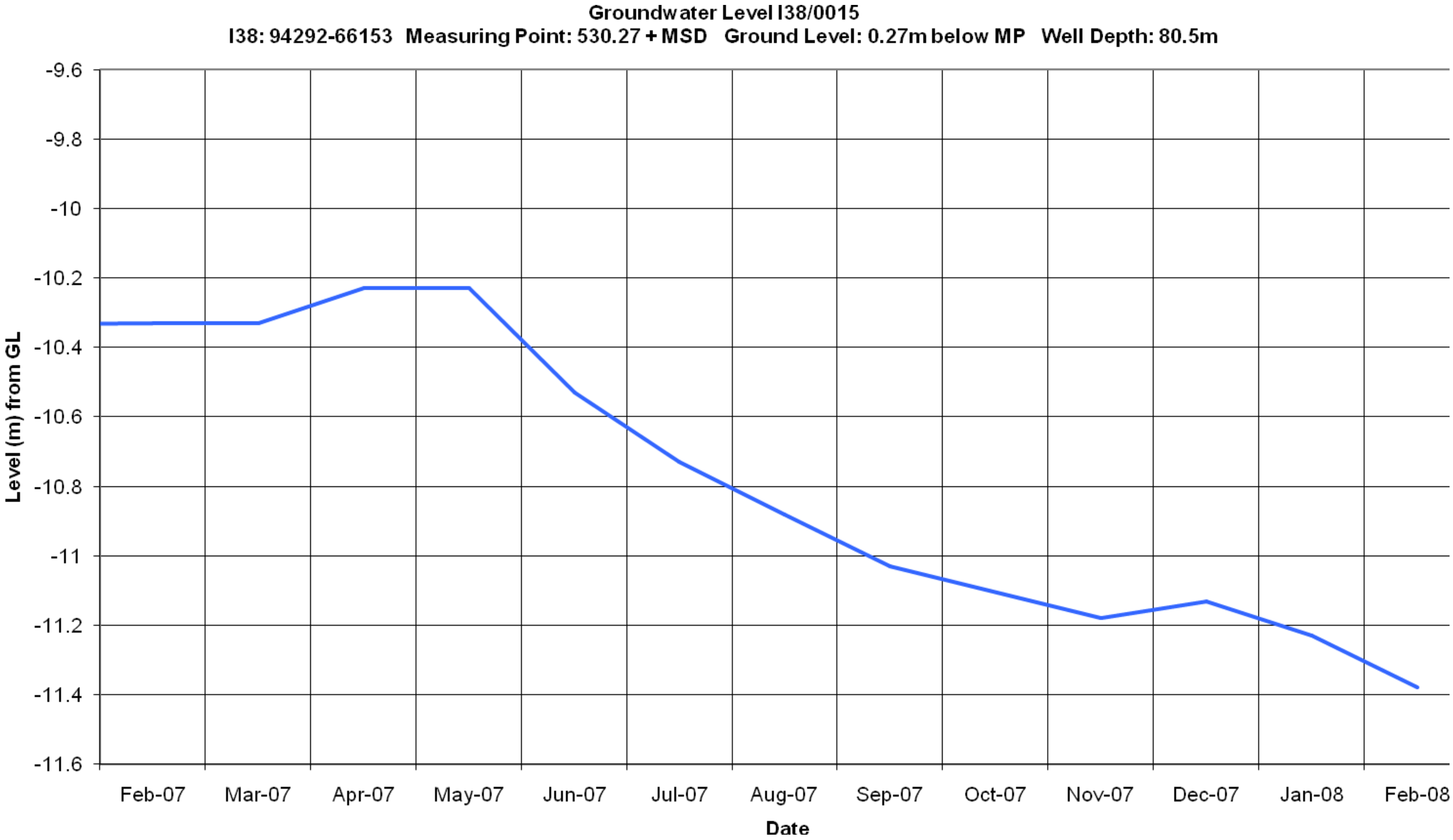

Groundwater Level I37/0032
I37: 07794-80352 Measuring Point: 702.00 + MSD Ground Level: 1.13m below MP Well Depth: 33.5m
Level (m) from GL
-32
-32.2
-32.4
-32.6
-32.8
-33
-33.2
-33.4
-33.6
Bottom of Well
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

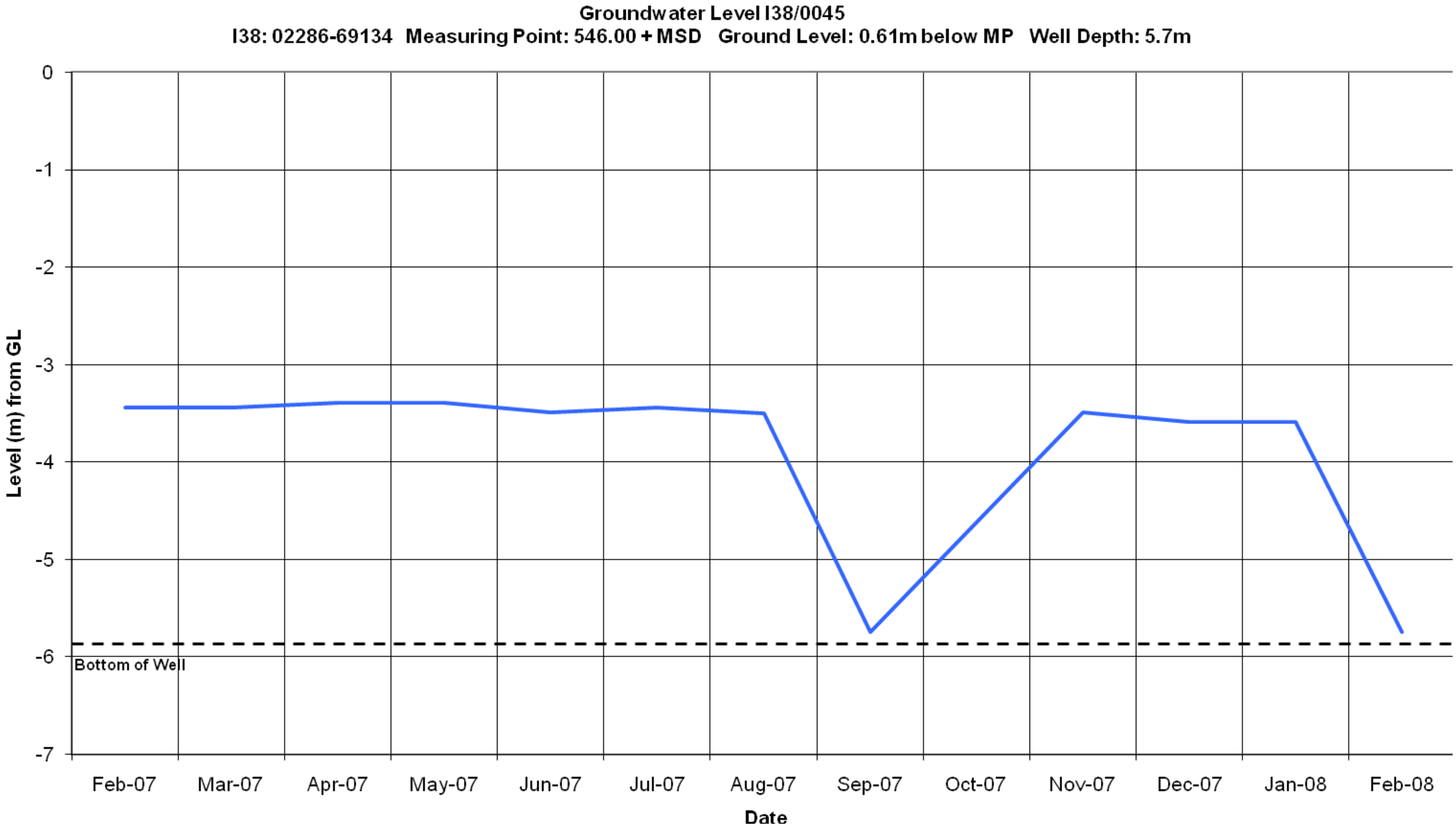

Groundwater Level I38/0003
I38: 05769-57621 Measuring Point: 533.59 + MSD Ground Level: 0.59m below MP Well Depth: 47.4m
0
-1
-2
-3
-4
-5
-6
-7
-8
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

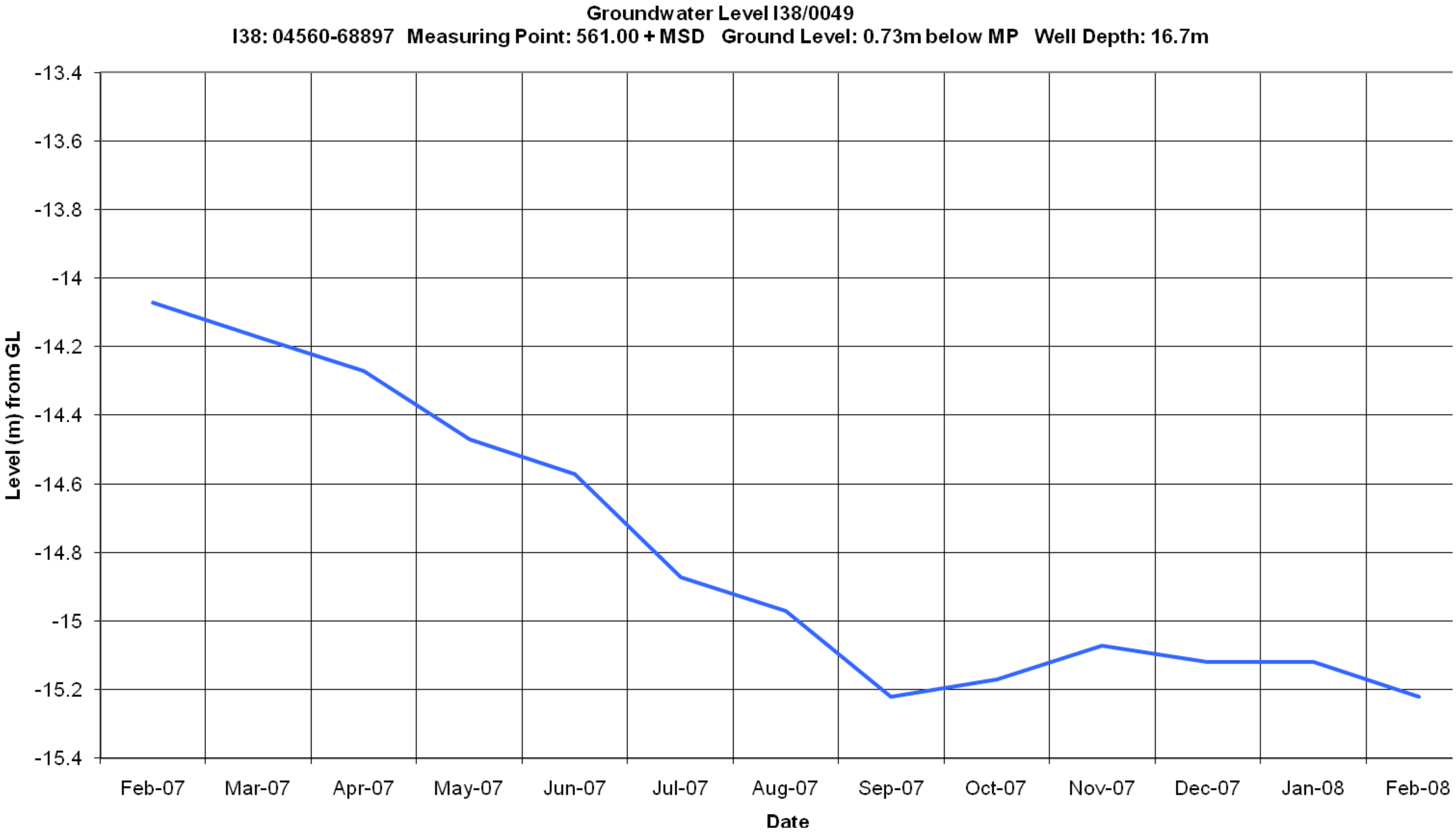

Groundwater Level I38/0004
I38: 0311-5152 Measuring Point: 538.00 + MSD Ground Level: 0.33m below MP Well Depth: 27.7m
Level (m) from GL
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

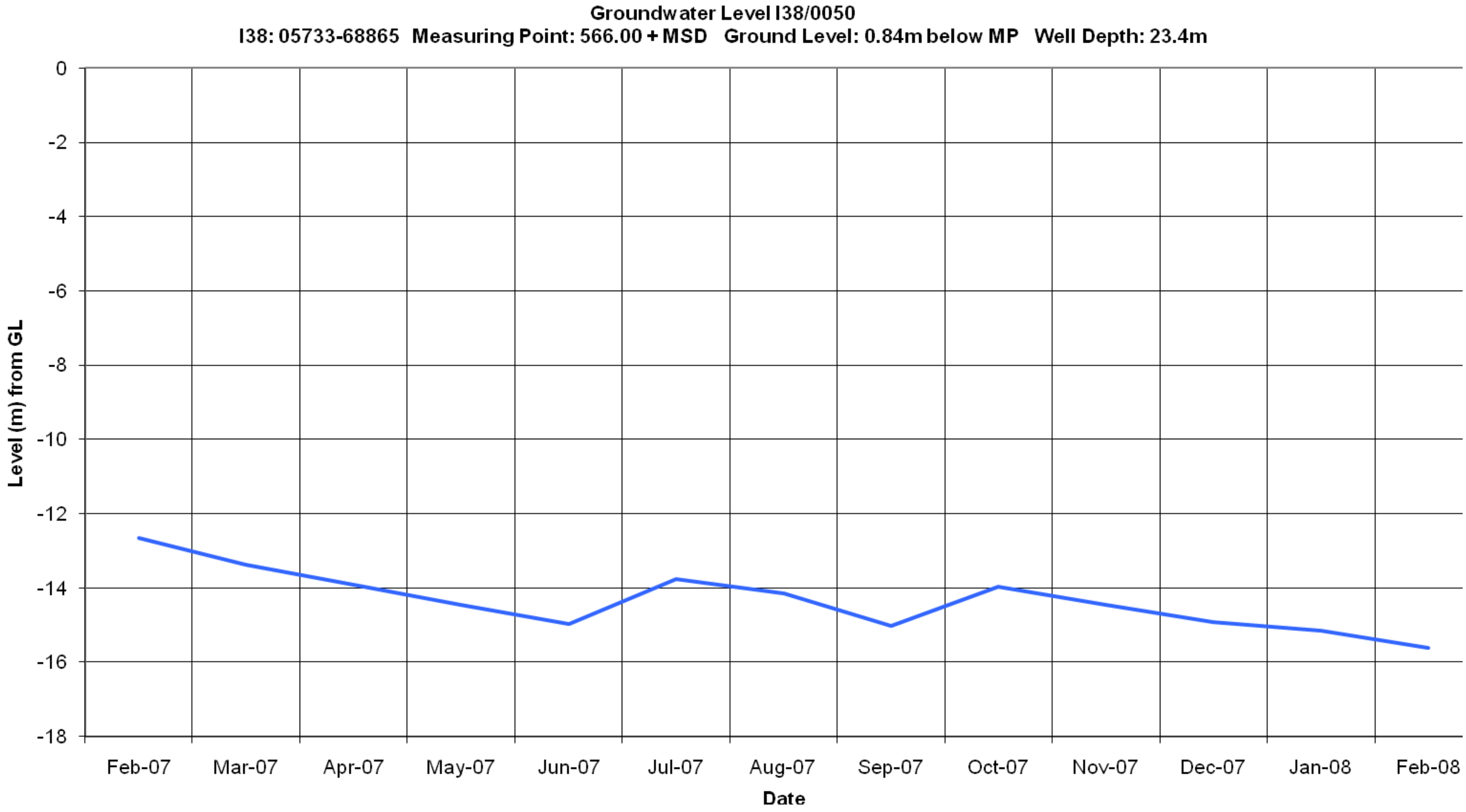

Groundwater Level I38/0012
I38: 93791-68555 Measuring Point: 562.47 + MSD Ground Level: 0.47m below MP Well Depth: 105.0m
Level (m) from GL
-32
-32.5
-33
-33.5
-34
-34.5
-35
-35.5
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date
Questionable Reading

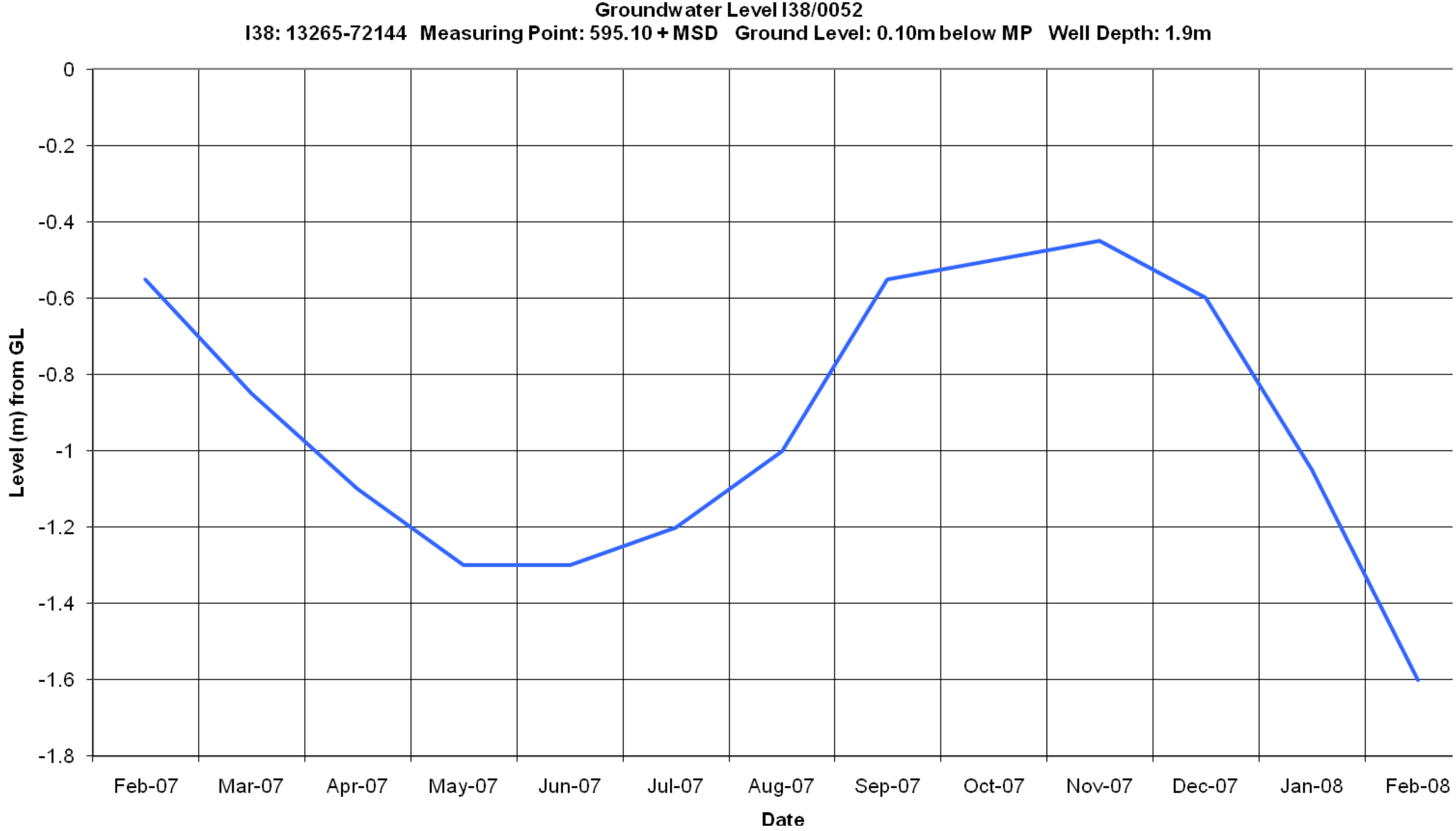

Groundwater Level I38/0014
I38: 95280-65404 Measuring Point: 528.00 + MSD Ground Level: 0.70m below MP Well Depth: 24.7m
0
-1
-2
-3
-4
-5
-6
-7
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

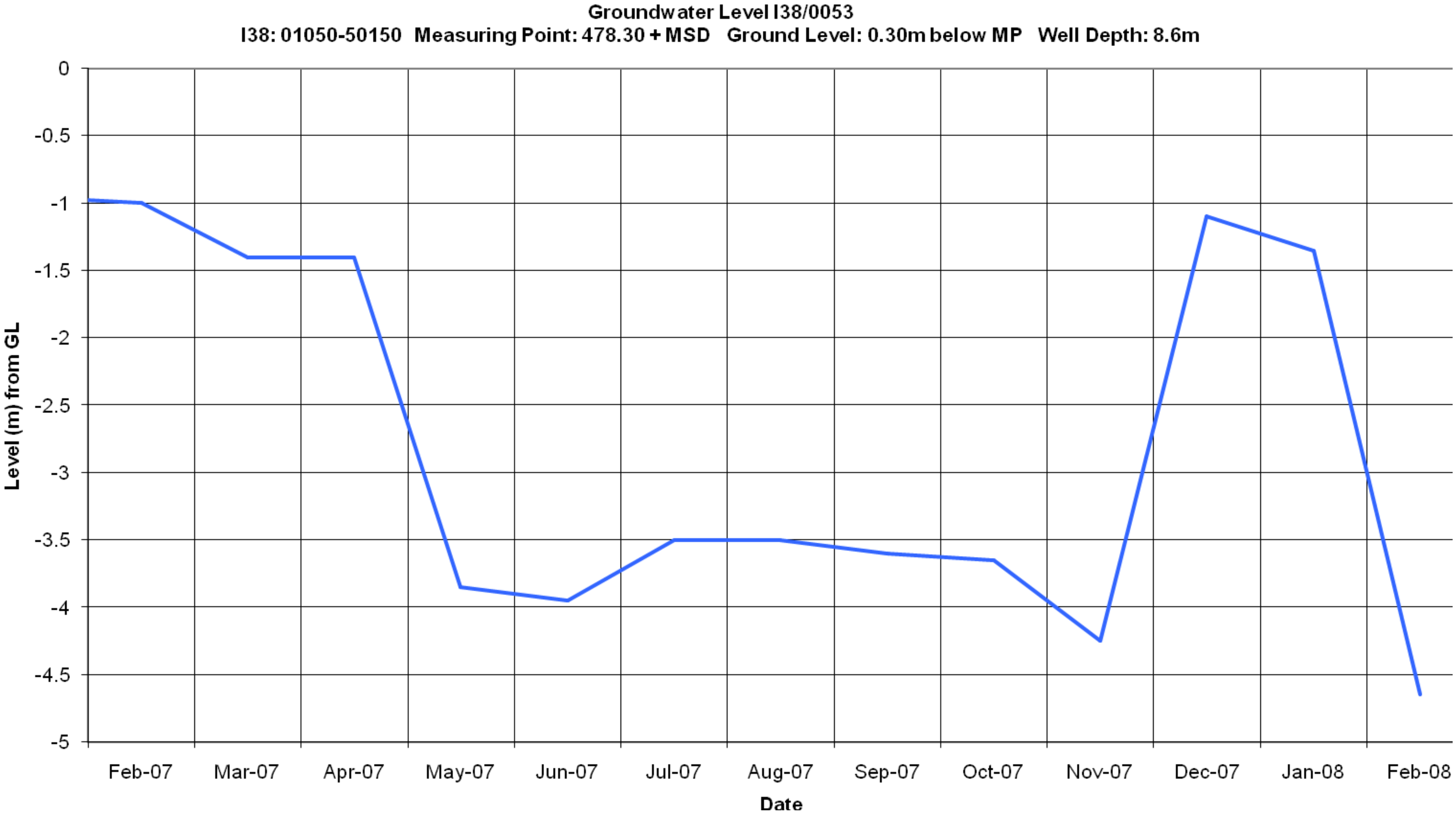

Groundwater Level I38/0015
I38: 94292-66153 Measuring Point: 530.27 + MSD Ground Level: 0.27m below MP Well Depth: 80.5m
Level (m) from GL
-9.6
-9.8
-10
-10.2
-10.4
-10.6
-10.8
-11
-11.2
-11.4
-11.6
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

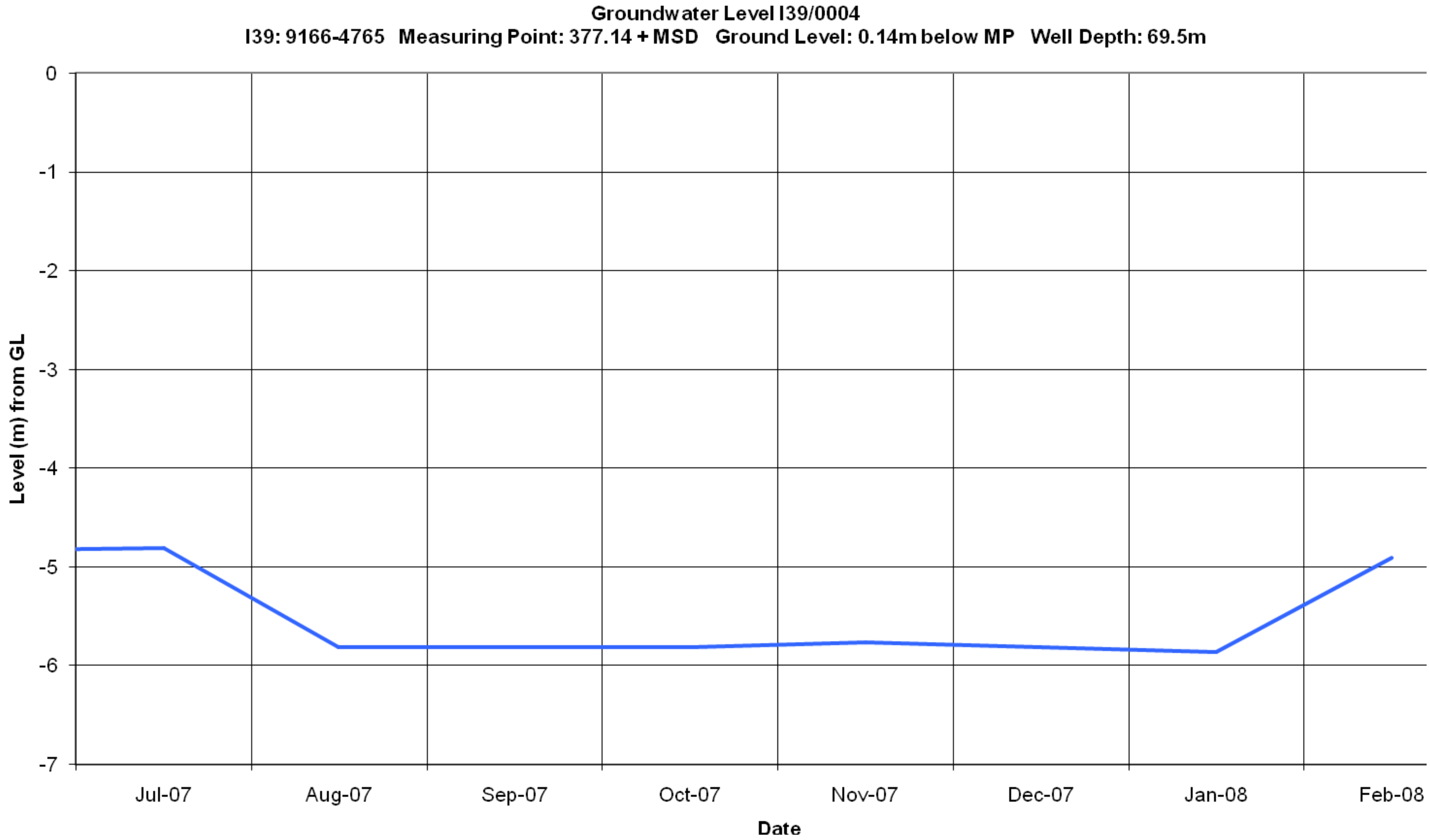

Groundwater Level I38/0045
I38: 02286-69134 Measuring Point: 546.00 + MSD Ground Level: 0.61m below MP Well Depth: 5.7m
0
-1
-2
-3
-4
-5
-6
-7
Level (m) from GL
Bottom of Well
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

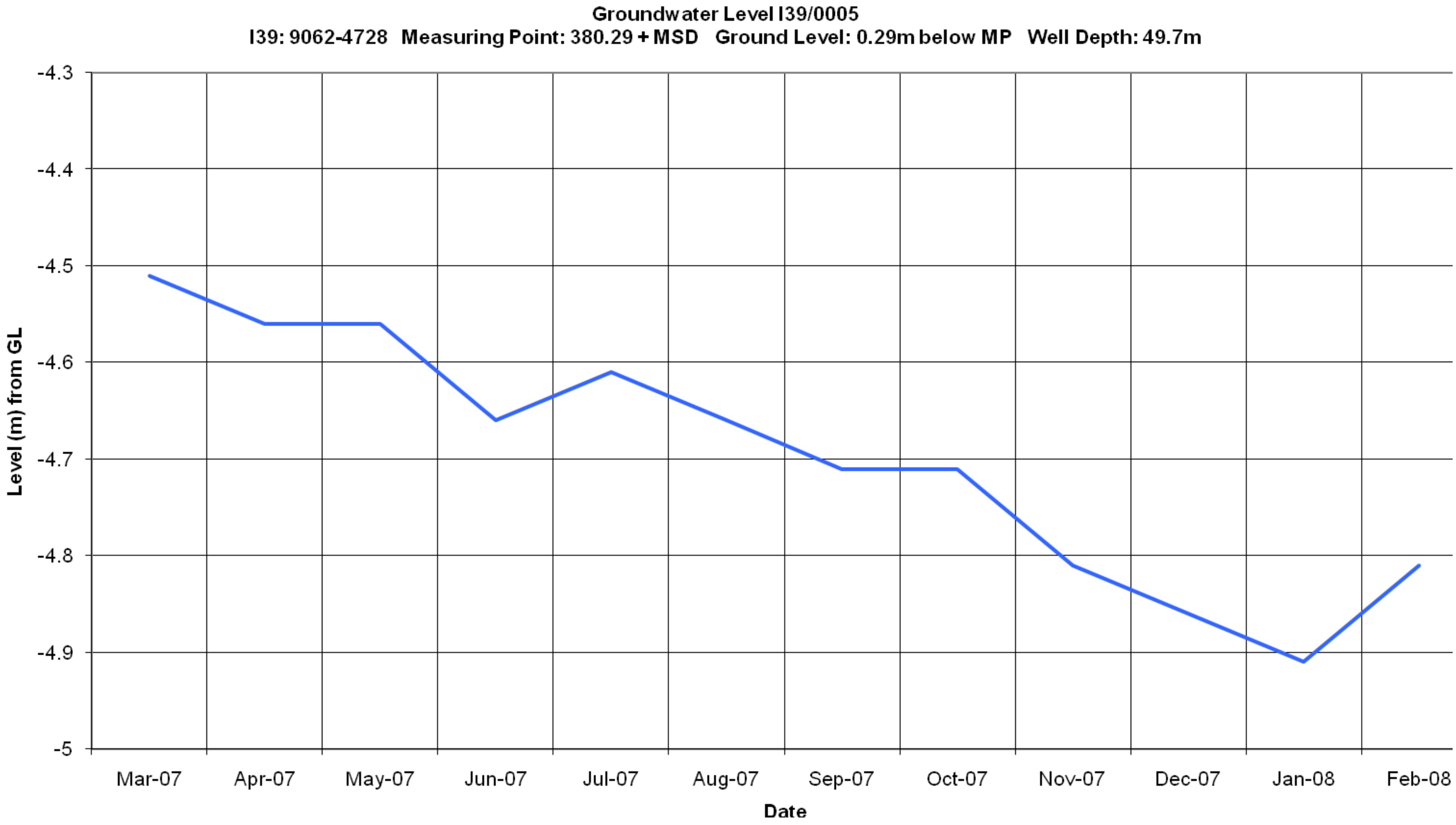

Groundwater Level I38/0049
I38: 04560-68897 Measuring Point: 561.00 + MSD Ground Level: 0.73m below MP Well Depth: 16.7m
-13.4
-13.6
-13.8
-14
-14.2
-14.4
-14.6
-14.8
-15
-15.2
-15.4
Level (m) from GL
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level I38/0050
I38: 05733-68865 Measuring Point: 566.00 + MSD Ground Level: 0.84m below MP Well Depth: 23.4m
Level (m) from GL
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

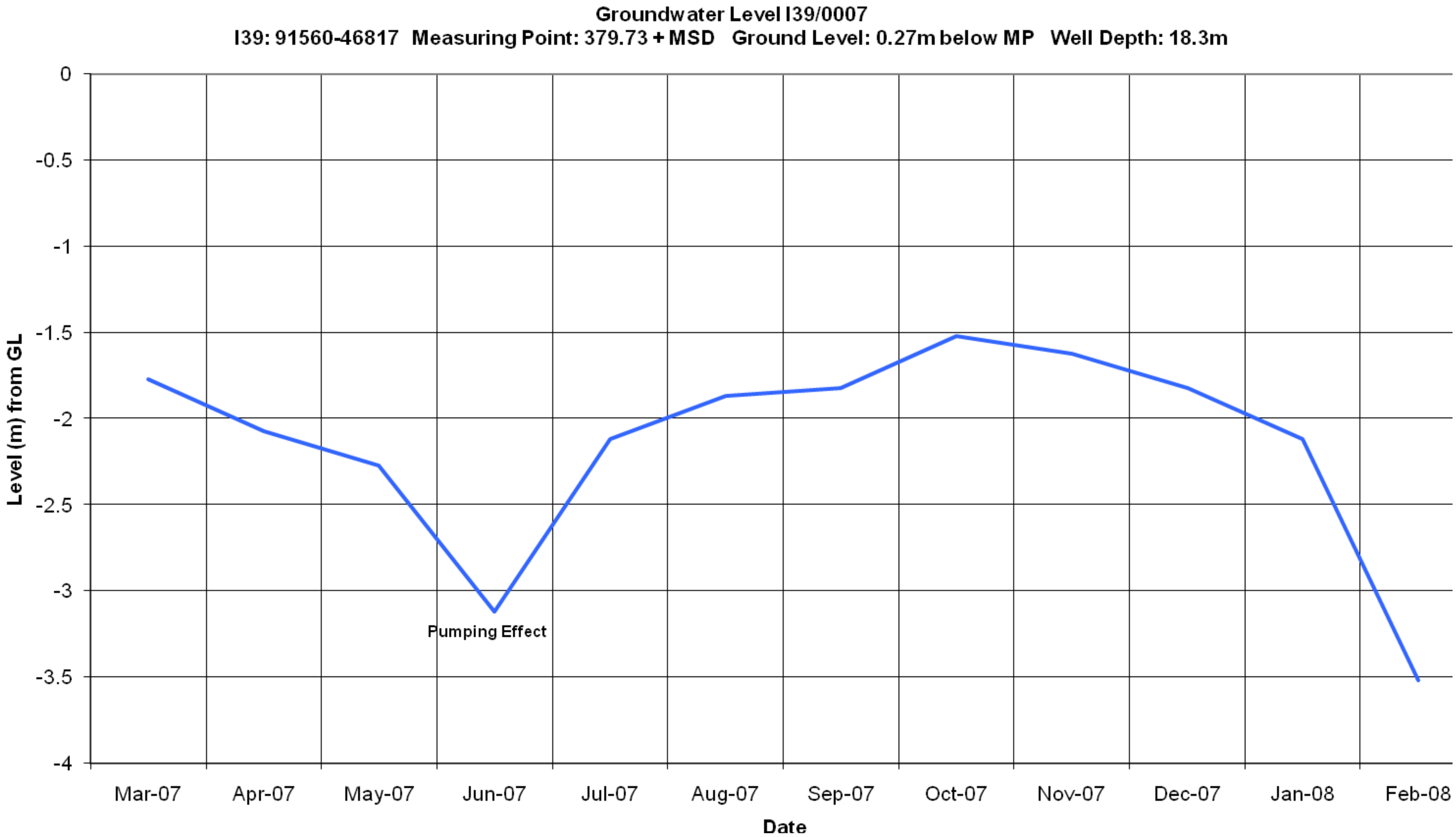

Groundwater Level I38/0052
I38: 13265-72144 Measuring Point: 595.10 + MSD Ground Level: 0.10m below MP Well Depth: 1.9m
Level (m) from GL
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level I38/0053
I38: 01050-50150 Measuring Point: 478.30 + MSD Ground Level: 0.30m below MP Well Depth: 8.6m
Level (m) from GL
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
Feb-07
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date


Groundwater Level I39/0004
I39: 9166-4765 Measuring Point: 377.14 + MSD Ground Level: 0.14m below MP Well Depth: 69.5m
0
-1
-2
-3
-4
-5
-6
-7
Level (m) from GL
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

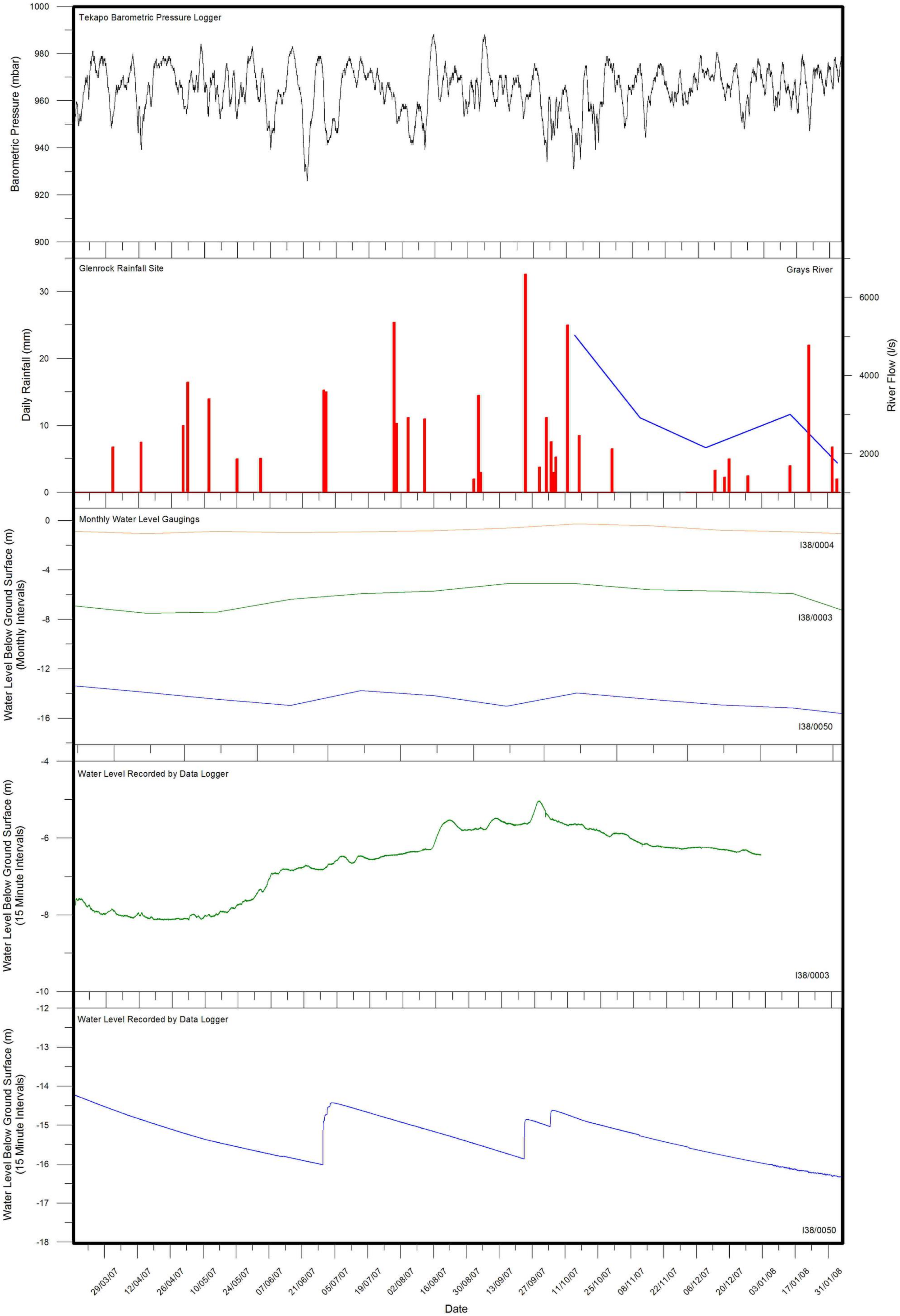


Groundwater Level I39/0005
I39: 9062-4728 Measuring Point: 380.29 + MSD Ground Level: 0.29m below MP Well Depth: 49.7m
-4.3
-4.4
-4.5
-4.6
-4.7
-4.8
-4.9
-5
Level (m) from GL
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

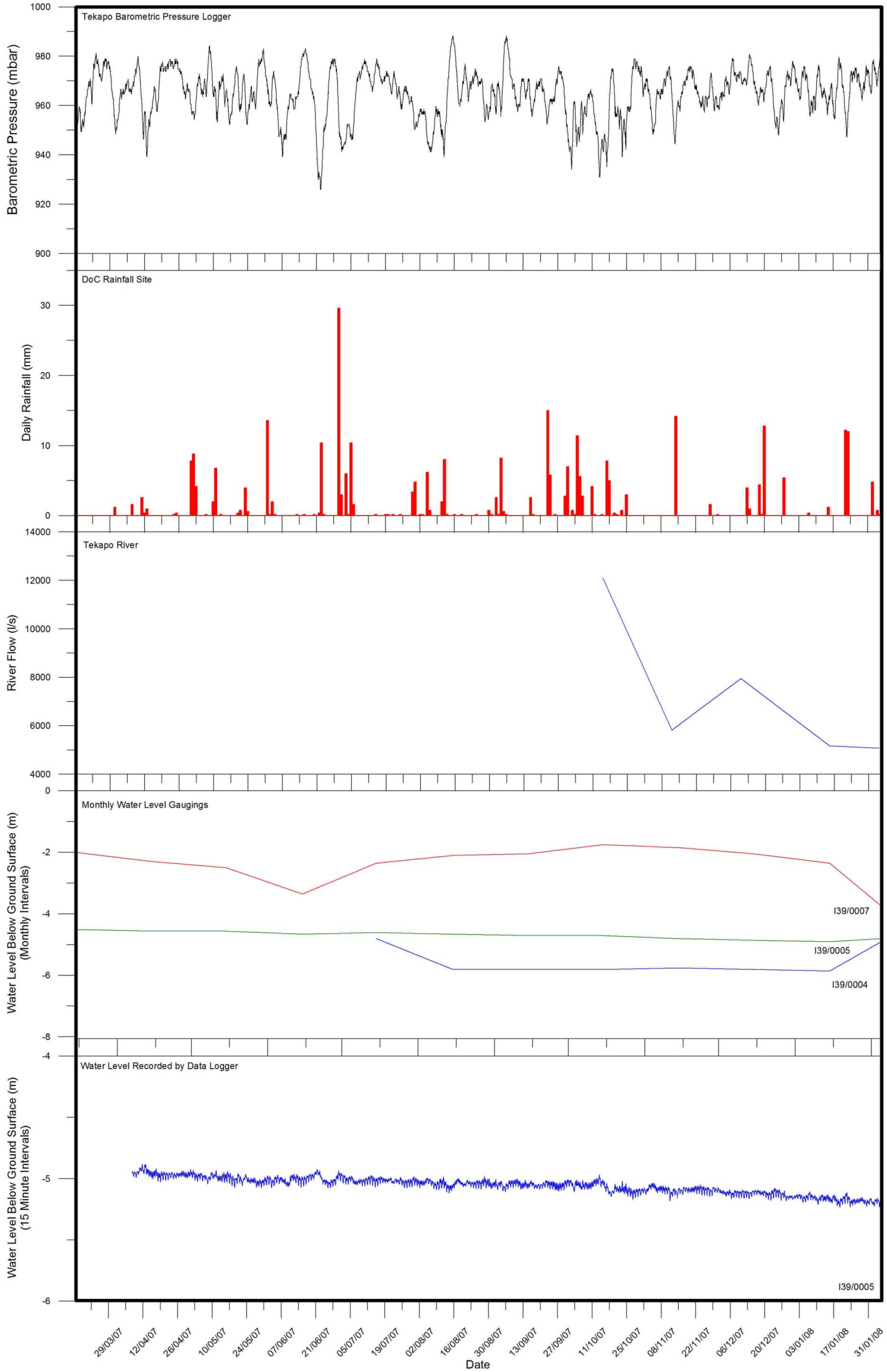

Groundwater Level I39/0007
I39: 91560-46817 Measuring Point: 379.73 + MSD Ground Level: 0.27m below MP Well Depth: 18.3m
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
Level (m) from GL
Pumping Effect
Mar-07
Apr-07
May-07
Jun-07
Jul-07
Aug-07
Sep-07
Oct-07
Nov-07
Dec-07
Jan-08
Feb-08
Date

Appendix 7H

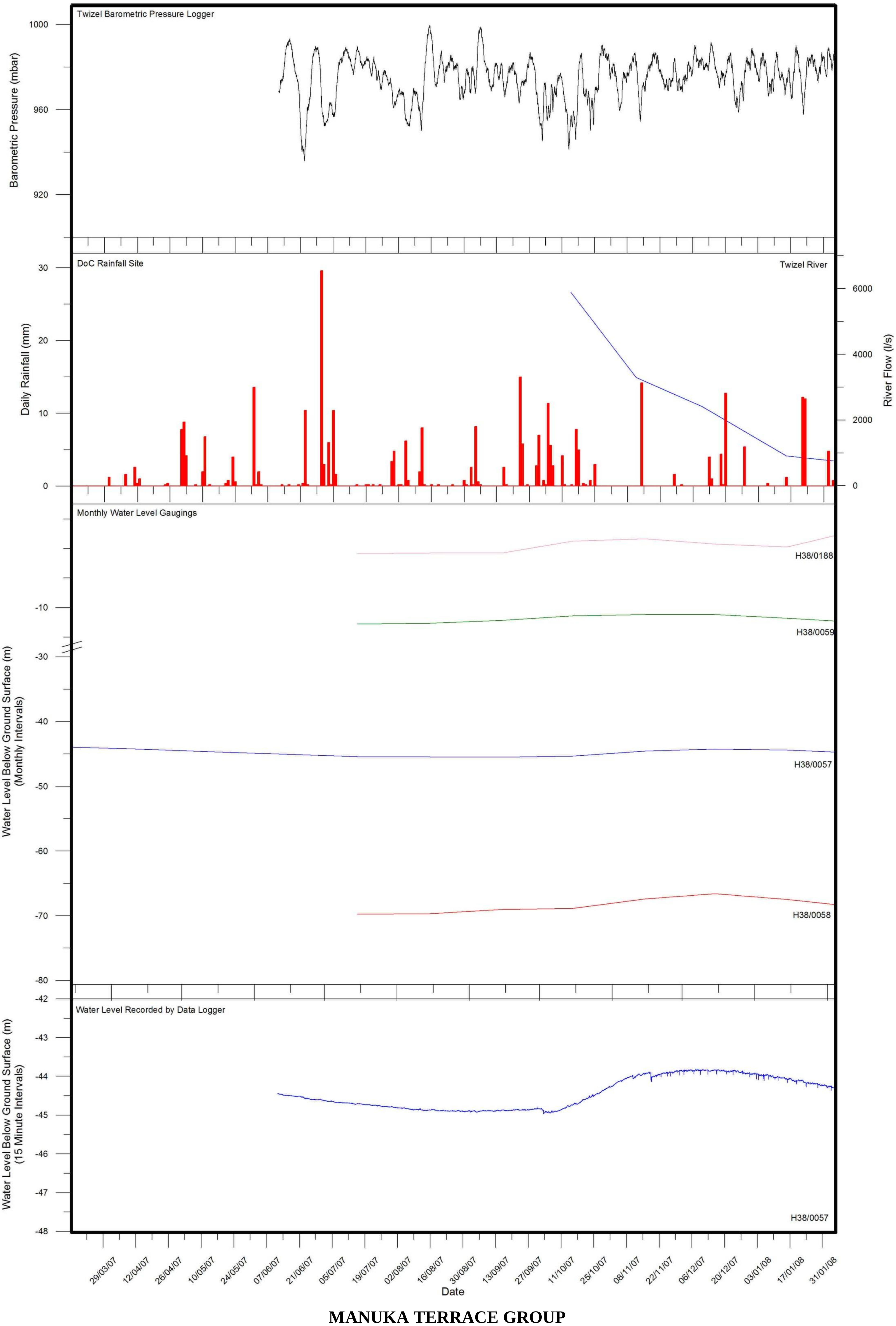
Hydrographs



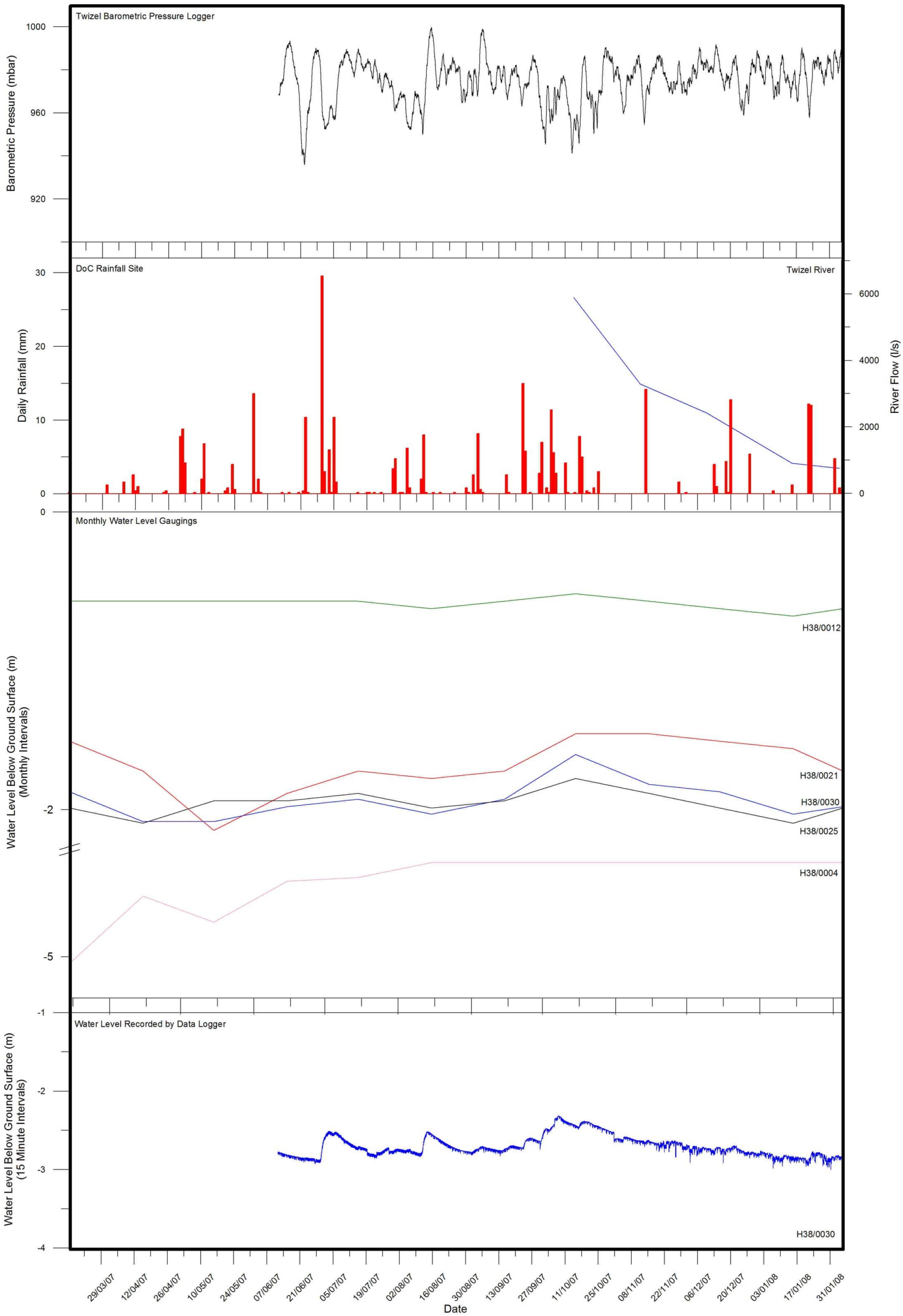
GRAYS FLATS GROUP



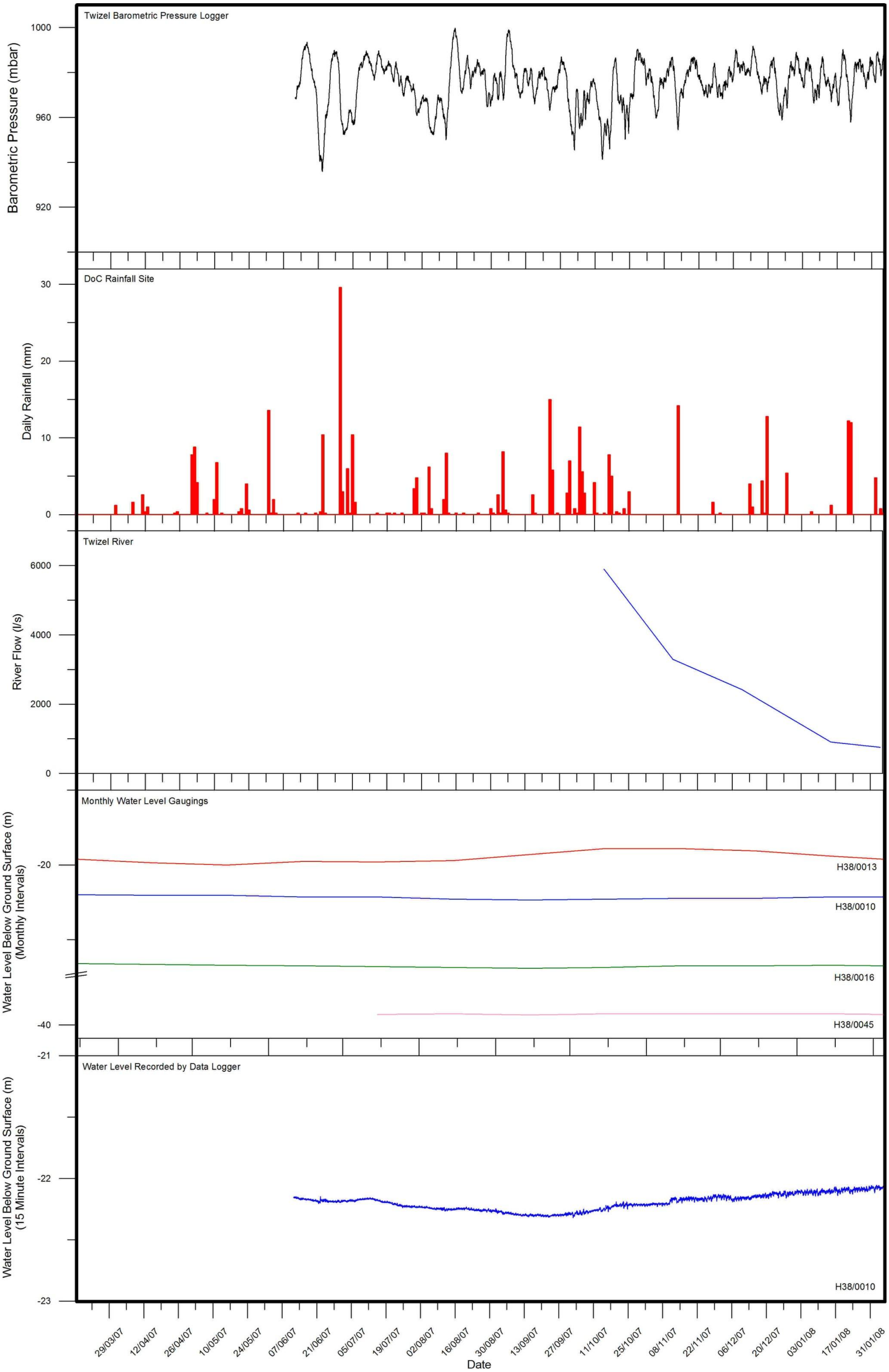
HALDON GROUP



MANUKA TERRACE GROUP



BENDROSE GROUP



TUSSOCK BEND GROUP